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A BUREAU OF SHIPS LABORATORY

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PREFACE

The transpolar crossing of the Arctic Ocean by the USS NAUTILUS (SSN 571) during August 1958 demonstrated the capability of submarines to operate under the arctic ice pack. Consequently, the "SECRET" classification barrier which surrounded arctic submarine studies the past twelve years has disappeared. Furthermore, the summer and winter polar operations by the USS SKATE (SSN 578) have demonstrated the capability of the modern submarine to surface within the ice canopy at any time.

The report, "The Polar Submarine and Navigation of the Arctic Ocean," was first issued November 1948. It is reprinted without any changes (except for the inclusion of an addendum written in May 1950), because editing in 1959 would be applying hindsight and thus negate any lessons to be learned from comparison of 1948 plans and programs with actual events that have followed. Parts of the report are of historical interest only; other parts are still pertinent to in-ice submarine operations.

Waldo Lyon
May 1959

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NEL Problem No. 2A5
17 May 1950

ADDENDUM: COMMENTS AND MODIFICATIONS

Since the preparation of this report, further work has changed certain considerations that were presented. This addendum is a summary of the more recent work and planning.

The prime requirements for the submarine modification are simple to state but do conflict with conventional problems of buoyancy and stability. The requirements are:

1. The submarine must be capable of being "topped" (under the ice) exactly analogous to being "bottomed."
2. Some snorkel method capable of boring through ice.
3. Scanning sonar for under-ice navigation and topside echo sounder for vertical ascents into lakes or "topping" the boat under-ice.

The "turtle-back" requirement (item (1) above) is any method which permits the hull to rest underneath the ice with positive buoyancy. It is believed that the ice boring snorkel (item (2) above) presented in the subject report (figure 66) can be simplified. We are now setting up in laboratory arctic rooms a full scale pilot experiment to test ice boring methods specifically intended to aid in the design of ice snorkels. The favored method depends on warm water erosion of the ice, i. e., the boring tube consists of two concentric tubes (i. d. of inner tube is 6 inches), with a small spacing between tubes. Warm salt water is pumped by a standard trim pump up through the spacing between the tubes and is forced through nozzles around the periphery at the top of the tube. The pressure from the trim pump will also produce the necessary lift to force the tube through the bored hole. From further studies of sea ice structure, it is expected that erosion will very effectively assist the melting produced by the warmed water. This method results in a simple, double-walled tube with no required mounting of electrical cables, connections, or devices on the tube itself. It is our intent to have realistic data from these tests available by the end of the year.

The QLA scanning sonar has been found to be the most successful sonar for evaluating the ice canopy and under-ice navigation. A QLA equipment is, therefore, required. Ascents into ice lakes are controlled by a topside echo sounding system as suggested in the report. The Navy Electronics Laboratory has assembled a five-unit echo sounding system which consists or five Type NK transducers (frequencies: 26.2, 23.7, 21.2, 18.6, and 16.2 kc). The system is simple and rugged, and should fulfill the diving requirements. We had hoped to evaluate this system on a submarine cruise to the Beaufort Sea during the summer of 1950. However, this cruise has been cancelled, and evaluation will be partially checked by conventional dives off San Diego within the next six months.

In addition to the principal items of the second paragraph above, there are, of course, numerous special items, for example, any improvements in gyrocompasses to aid navigation at high latitudes and installation of a large inboard vent on safety tank for control of vertical ascents. (cf. patrol report of USS CARP, SS-338/A4-3 Ser 013, of 23 September 1948).

ABSTRACT

The intent of the Navy's high-latitude studies, both accomplished and planned, is the design of a polar ocean submarine capable of operating to any part of the Arctic Ocean. Such a submarine must be developed before the undersea physicist can explore the entirely new field of research that confronts him in the arctic seas. The problem faced in this research, then, splits into two major phases, (1) the design of a submarine for under-ice operations, and (2) the oceanographic and sonar studies of the polar seas.

Both phases of the problem were considered by Laboratory personnel who took part in submarine voyages in 1946-47-48. Their observations of sea ice, temperature-density, and ocean-bottom conditions, and of the performance of the submarines and special navigating equipment have delineated those problems whose solutions are prerequisites for the polar submarine. The observations are evaluated with a view to giving the basis for the choice of the most profitable research methods and relative priorities of arctic problems. Under-ice dives, stationary ascents, sonar scanners, and buoyancy control are discussed, and the schematic design for the modification of a fleet-type submarine into an under-ice research submarine is presented.

Several definite conclusions were reached and may be summarized briefly as falling under four heads:

1. The Arctic Ocean is potentially navigable.
2. The realization of an under-ice submarine is within reach, and is far closer than had been envisioned.
3. Simple modification of a fleet-type submarine may supply 75 per cent of the research answers.
4. Such modification is urgent, as an interim measure, because of the long delay between the design and completion of a strictly under-ice submarine.

INTRODUCTION

The NAUTILUS in 1931 north of Spitzbergen made the first attempt to dive under ice. A complete discussion of the experiment has been given by Sir Hubert Wilkins and his associates and by the Naval Examining Board (ref. 1). The USS ATULE (SS403) on 28 July 1946 succeeded in penetrating a distance of 1000 yards under an ice field in Kane Basin but suffered a collision between the ice and the periscope shears. The patrol of the USS SENNET (SS408) with Task Force 68 in the Ross Sea, Antarctica, during January 1947 demonstrated the punishment that a submarine can take in heavy ice. During August 1947, the USS BOARFISH (SS327) maneuvered under the ice in the narrow confines of the Chukchi Sea for a total of ten hours in three dives, or a distance of about 30 miles. The USS CARP (SS338) successfully conducted *vertical* dives and ascents in ice lakes of the Chukchi Sea during September 1948. Considerable oceanographic research was achieved on all cruises. The U. S. Navy Electronics Laboratory participated in the SENNET, BOARFISH, and CARP patrols.

Reports on the oceanographic observations in the arctic and antarctic areas have been published by the Laboratory (refs. 2 and 3). The three submarine cruises have been covered in patrol reports by the respective commanding officers (refs. 4, 5, and 6). This report is split in two major parts; first, descriptive data and qualitative interpretations of the three cruises, and second, a program for the next experiment, namely, deep penetration of the Arctic Ocean.

ANTARCTIC OCEAN: SENNET PATROL

The USS SENNET was attached to the Central Task Group, Task Force 68, which includes the USS MT. OLYMPUS (AGC8), USS MERRICK (AKA97), USS YANCEY (AKA93) and USCGC NORTHWIND (WAG282). The group began passage through the ice pack in the Ross Sea on 31 December 1946. Its assignment was the establishment of an air-base on the Ross Ice Barrier.

The ice pack was found to be very heavy and extensive. Though a helicopter was employed by the icebreaker to give a wide area of search, a lead could not be found along the 180th meridian where one normally appears. The ice pack extended from the Barrier to Scott Island and was still integrated though the summer was well along. The task group formed in column in the order NORTHWIND, MERRICK, YANCEY, MT. OLYMPUS, and SENNET, and an attack was made on the heavy pack. After a few days, it became apparent that the passage would be most difficult and that four ships were too many for one icebreaker to handle in ice of such severity. Obviously, the submarine was not required for the primary mission of the task group and was guided back to the vicinity of Scott Island by the NORTHWIND.

During the passage in and out of the ice pack, the submarine withstood many severe tests. The bow withstood unusual punishment, since it was necessary to ram ice on many occasions to force leads between brash and ice pans. Damage primarily occurred during towing operations by the NORTHWIND. Observations in excellent detail are given by Comdr. J. B. Icenhower in the patrol report of the USS SENNET (see p. 9, ref. 4). The ice conditions are illustrated in figures 1 through 10, and should be compared with examples of ice which were encountered in the Chukchi Sea (cf. figs. 24 to 36).

Ship handling in ice is concisely discussed by Comdr. Icenhower and is included as pertinent information in any consideration of the polar submarine (Appendix C). The CARP found the suggested techniques helpful during "in-ice" maneuvers in the Chukchi Sea.

Sonar Data

Sonar and radar observations were conducted in the vicinity of Scott Island along the northern edge of the ice pack. The recognition of various size pieces of ice (brash to bergs) was studied on both the scanning sonar (QLA) and the echo-ranging sonar (QB/QC). Runs were made on the surface and at periscope depth. Equipments carried by the USS SENNET are given in Table I.

Examples of observed ranges on various ice targets are given in Table II. Bottom reflections were not observed and sound ranges appeared to be limited during all trials by surface reverberations, which varied strikingly with the sea state and slight shifts in temperature gradients. Upward refraction is the dominant characteristic of the area and results in difficulties of very long ranges for surface targets, zero to poor recognition of deep targets, and the blanking out of contacts inside 1200 yards range by surface reverberation. These features are typical when positive gradients are present, and had been observed in British Columbia areas during winter months.

Reverberation bursts at ranges of 900 to 1100 yards and 2200 yards were very striking on both QLA and QB/QC during most tests, and the sonar operators often confused these bursts with ice contacts until they had had considerable coaching and experience. The modulation sweep (chirp) on the QB and tonal quality on the QLA were necessary and were used successfully to separate an ice target from the reverberation burst. Of course this separation depended on the size of the ice target and the sea state.

TABLE I — EQUIPMENTS ON USS SENNET

Equipment Purpose	Model	Serial	Location of Controls	Location of Transducer (or Hull Unit)	Remarks
Supersonic listening and echo ranging	WCA-2	51			
	QC/JK		Conning	Port-topside shaft	No troubles
	QB		Conning	Starboard-bottom-side	TDM modification removed
Fathometer	NGA-2	119	Control	Keel	
Scanning sonar	QLA	20	Conning	Port-bottomside	Training troubles
Echo sounder for depth below ice	SESE III-3	3180	Fwd. torp. rm.	Bow-topside	Transducer failed
Sonic listening	JT		Fwd. torp. rm.	Starboard-topside	
Bathythermograph	OCN	436	Conning	Shears	
Buoyancy control and sonar ranges (including salinity)	CXJC-1 (CTB-X55202)	X-1	Conning and Control	Shears and keel	

On one or two days, the sea state was zero (nearly glassy), though a slight swell was present; the lack of surface reverberation was even more striking since one had become accustomed to persistent surface reverberations. The sea was scattered with small chunks of ice, about 1 foot by 1 foot in size. Each piece gave a distinct, sharp echo to ranges greater than 2000 yards.

The ambient noise level observed on the QB and QLA appeared to be very low while lying to in ice areas. No listening contacts either of ice or biological origin were observed. During dives the noise level on the JT equipment was noticeably low and no contacts were reported. This condition was also observed in arctic areas.

It is of interest to calculate the characteristics of sound propagation for the antarctic area. It had been expected that oceanographic stations would be taken by the USCGC NORTHWIND in conjunction with sonar measurements on the USS SENNET. However, since the latter vessel operated alone no coordination of data could be accomplished. Examples of bathythermograms taken by the NORTHWIND are shown in figure 11, and are grouped in observations to the north of the ice pack and within the pack. An analysis of bathythermograms from Operation Highjump has been carried out by Scripps Institution of Oceanography and the Oceanography Section of this Laboratory (ref. 2).

A prominent characteristic of the vertical thermal structure is the existence of a positive gradient below 200-foot depth, the influence of which was distinctly observed during echo-ranging trials. Calculation and description of the sound field are given in Appendix B.

Buoyancy Control

The oceans which surround Antarctica are immense. Submarine operations were essentially in deep ocean water, and complexities of buoyancy control were neither expected nor observed. The variation of temperature or salinity with depth or position is not great. Localized, short-time variations occur in the vicinity of melting ice, or in the mixing at the Antarctic Convergence, which may cause unexpected shifts in buoyancy of small magnitude. These were observed; however, there is ample sea room and depth in which to make corrections, a sharp contrast to conditions in the very shallow Chukchi Sea.

ARCTIC OCEAN: BOARFISH AND CARP PATROLS

The USS BOARFISH (SS327) was part of a submarine force which included the USS NEREUS (AS17), the USS CAIMAN (SS323), the USS CABAZON (SS334), and the USS CHUBB (SS329). The force operated in the Chukchi Sea during August 1947 under the immediate command of Rear Admiral A. R. McCann. The track chart of the BOARFISH is shown in figure 12.

An oceanographic survey was conducted from the USS NEREUS. Stations were taken at every opportunity across the Bering Sea and near the ice in the Chukchi Sea. Some inshore work was accomplished along the Alaskan coast. Though the results are very important to submarine operations, they are reported by separate report (ref. 3), in order to present the oceanographic material in a unified form and to avoid classification of material useful to other problems.

The USS CARP (SS338) operated within the pack ice from 3 to 11 September 1948 in the vicinity of 167° W. and 72° N. The pack ice was penetrated to a distance of about 54 miles to the edge of the consolidated arctic pack. The major part of the time was spent in vertical dives and ascents within ice lakes. The track chart (fig. 13) indicates the position of brash ice and arctic pack.

It is well to keep in mind certain general but obvious features of the Bering and Chukchi Seas (fig. 12). The Bering Sea is virtually land-locked by the Aleutian Island chain; however, deep water lies along most of this chain and the western part of the sea, and is an integral part of the Pacific Ocean The northern half of the Bering Sea and the Chukchi Sea are very shallow, 15 to 30 fathoms, and delimit the winter and summer extremes of the ice pack. Mostly, this shallow bottom is soft mud. Except for areas of sand and gravel in the vicinity of the Bering Strait, it is strikingly flat for great distances. The temperature and salinity structure of the Chukchi Sea during summer is very complex and variable, and exhibits unusually intense stratification. This complexity is illustrated by the bathythermograms of figure 14. The contrast between bathythermograms taken on the two patrols is striking. The extreme layering appears to be a mixing of warm Bering Sea water, cold arctic basin water on the bottom and melt water on the surface. The arctic basin water (less than 30° F.) was not observed during the CARP patrol. A continuous record of the surface temperature and salinity and the depth across the Chukchi and Bering Seas is shown in figure 15. The significance of the record is no more than an illustration of the variability of water structure. Temperature-salinity profiles computed from oceanographic stations aboard the USS NEREUS are given in figures 16 and 17. The observations are further discussed in the oceanographic report (ref. 3). The required buoyancy changes to maintain a 2100-ton submarine in trim from a depth of 50 feet to indicated depth are illustrated in figure 18 for three sections. The changes are computed from the oceanographic data assuming a diving rule of 1400 pounds per 100 feet. These data are only presented for illustration. An oceanographic synopsis of the Chukchi Sea is not justified.

Vertical Dives and Ascents

A principal question in the study of under-ice navigation is the buoyancy control. Stationary dives and ascents are prerequisite for successful operations in ice areas. The study of this question was the purpose of the CARP patrol, and its successful solution admits the practicability of submarine navigation across the Arctic Ocean. About fourteen vertical dives and ascents were made by the CARP. The ship-handling was excellent

TABLE II. EXAMPLES OF SONAR OBSERVATIONS

DATE	POSITION	SHIPS Speed (knots)	SHIPS Condition	SEA State	SEA Swell	BT DATA OR SURF TEMP	TARGET (Ht is in ft. above water)	EQUIPMENT	FIRST CONTACT (yards)	CONTINUITY OF CONTACT	ANGULAR MEASUREMENT OF TARGET (cut on cut off)	REMARKS
5 Jan		4	Surfaced			30° F	Growler, 10 ft. × 10 ft. × 2 ft. high	QB (24 kc)	1500*			Distinct surface reverberation
8 Jan	56° 55' S 179° 51' E	4	Surfaced	1	0	32° F.	Ice finger projecting from peak, 1000 yds. long, 3 ft. high	QLA	1500*†	Held as passed within 200 yds		Distinct portrayal on 1200-yd scale, permitting navigation by QLA alone. Pans 4 ft × 3 ft, × 3 ft gave distinct contacts at 500-yd range
10 Jan	67° 10' S 171° 23' W	4	Surfaced	1	0	32° F.	Tabular iceberg, 350 yds. in width	QB (24 kc)	4000*	Red light contact, 1800 yds. 100% recog 4000 yds. to 700 yds.	At 1100 yds., 25° by red light, 18° by periscope, 35° by audible cutoff	Surface reverberation high inside 1500 yds requiring modulated signal to get good identification against surface reverberations
11 Jan	66° 51' S 171° 59' W	4		0	5	33 F.	Bergy bit, 30 ft wide, 20 ft high	QB (24 kc)	3200* 25% recog.	3000 yds., 100% recog. 1700 yds., red light contact. Contact held as target passed abeam at 300 yds		No false echoes reported except one probable whale
							Iceberg, 800 ft. wide, 100 ft. high	QB	3850* 60% recog	3000 yds., 100% recog. 1600 yds., red light (100%)	At 1600 yds., 13° by red light, 10° by periscope	Background noise level exceptionally low
							Iceberg, 1200 ft wide, 125 ft. high	QB	4200	3700 yds., 25% recog. 3000 yds., 100% recog. 1900 yds., red light (100%)	At 3000 yds., 14° by audible cutoff, 8° by periscope	
							Bergy bit, 60 ft. wide, 20 ft. high	QB	2200* 25% recog.	2100 yds., 40% 1800 yds., 100% (no red light contact)		Audible contacts only, low intensity but distinct
							Bergy bit, 15 ft. wide, 5 ft. high	QB	550*			Observed only by modulated signal (chirp), since surface reverberation high with intense burst between 900 and 1100-yd range
15 Jan	67° 19' S 179° 42' E	3	Periscope depth	1	0	33° F.	Bergy bits and growlers 20 ft wide, 4 ft. high	QC	300	All contacts 100% audible recog. Not maximum ranges but observed ranges as passed through area of scattered ice		
							10 ft wide, 2 ft. high		600			QB performance inferior to QC probably due to topside mounting of QC
							40 ft wide, 10 ft high		2400			Reverberation not unusually high, "chirp" signal not required
							2 ft wide 1½ ft. high		700			
							6 ft. wide, 1½ ft high		800			Background noise level very low
							15 ft wide, 3 ft high		1000			
17 Jan.	67° 17' S 179° 36' E	2.5	Periscope depth and 100 ft	1	0	32° F BT Isothermal	No targets	QC QB	No false reports			Once surface reflection was reported between 500 and 1000 yds on QC, eliminated by modulated signal on QB

18 Jan	67° 20' S 179° 2' W	2.5	Submerged	1	0	32° F. BT Isothermal	Growlers, 8 ft wide, 2 ft high	QC	600*			Background noise strikingly low. One false report at 800 yds surface reflection. Few mushy echoes, not consistent, believed to be whales
							4 ft. wide, 1½ ft. high		850*			
							Bergy bit, 60 ft. wide, 40 ft. high		1700*			
20 Jan	67° 15' S 179° 31' E	4	Surfaced	1	1	33° F.	Bergy bit, 30 ft wide, 8 ft. high	QB	1500*	1100 yds., 100% recog. Contact carried into 500 yds.		Modulation (chirp) required inside 1200 yds. Reverberation strongly audible out to 3000 yds., bursts at 1100 and 2100 yds.
		2.5	Periscope			Isothermal 0 to 70 ft.	Growler, 4 ft. wide, 1½ to 3 ft high	QLA	600*†	Held as passed astern to 900 yds.		
						1° neg. grad. to 140 ft.		QB	500*	Held as passed astern to 900 yds.; lost in reverberations		Modulation (chirp) required, no contact by QC since did not have advantage of "chirp" signal
			150 ft.						No contacts			Surface reverberation appeared more intense than on previous trials
21 Jan	67° 19' S 179° 16' E	4.5	Surfaced	0	1	32° F.	Ten or more growlers 10 to 15 ft wide, 1 ft. high (mixed with brash)	QLA	600	Cont. held as passed		Each piece gave distinct contact, both audible and visual
								QB				Each target gave distinct echo, but targets much too numerous to evaluate for lack of presentation or plot
							Icebergs, 200 ft wide, 40 ft high	QB	3000*	Held during approach		
								QLA	1200			
							Iceberg, 450 ft wide, 20 to 60 ft high	QB	Max not observed		At 2000 yds., 20° by audible cutoff, 6° by periscope	
							Scattered pieces, 1ft. × 1 ft. 100 yds. apart	QLA	800-1000	Contact held on approach		Distinct contacts for each piece. (Note 3000-yd. scale inoperative)
								QB	2000	Held contact to 200 yds. without modulation		Distinct echo for each small piece. Reverberation remarkably less than on previous trials. Reverberation bursts at 1000 yds. absent, sea surface glassy
24 Jan	67° S 175° 28' W	3	Periscope to 350 ft.	0	4	6° neg. grad. Surf. to 200 ft.	NORTHWIND only target		No contacts — however, closest approach 2000 yds.			Note BT

* Audible
† Visual (red light on QB, CRO on QLA)

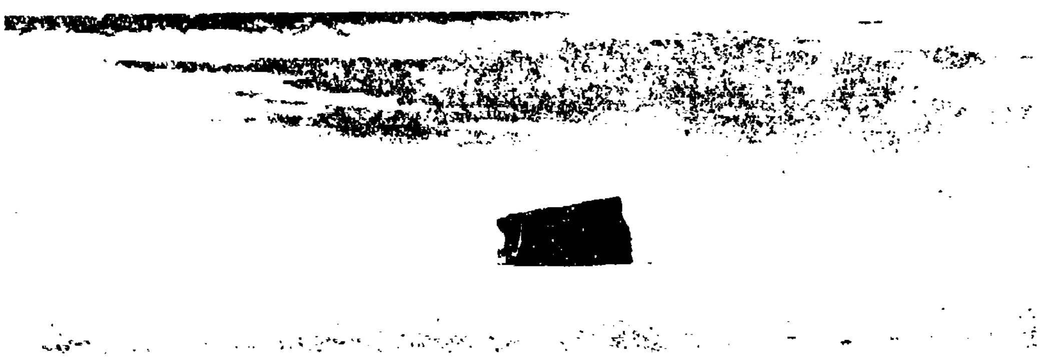


Figure 1. Iceberg, vicinity of Scott Island, height about 200 feet.

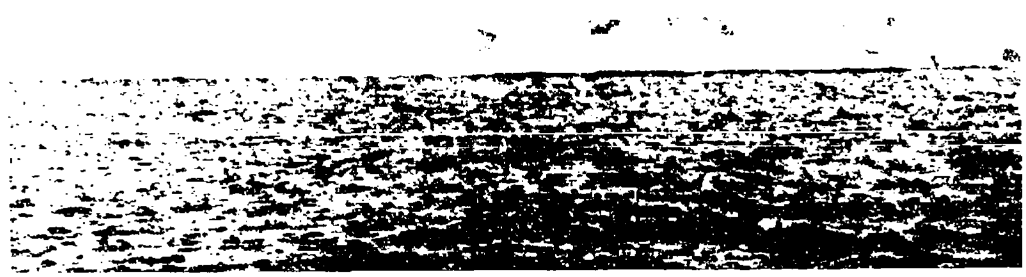


Figure 2. Large tabular icebergs, vicinity of Scott Island.

Figure 3. Passage through the Ross Sea ice pack.

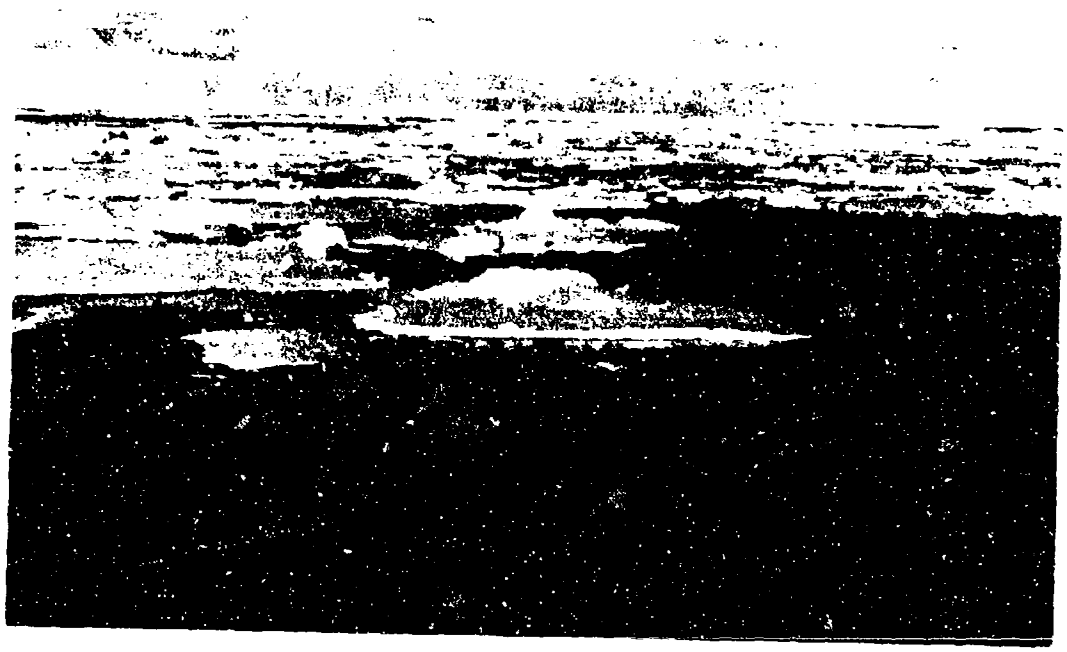


Figure 4. Passage through the Ross Sea ice pack.

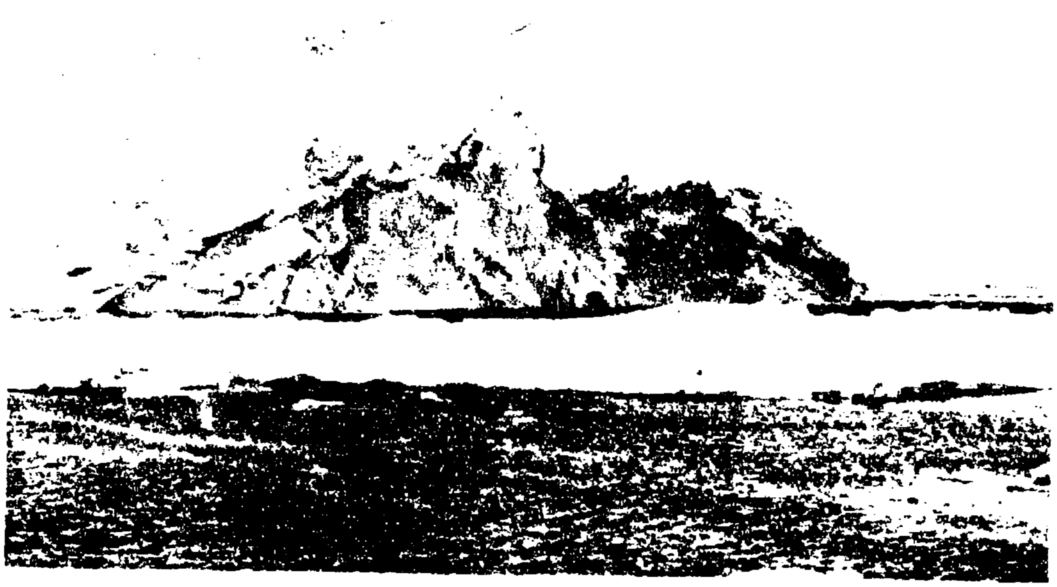


Figure 5. Iceberg passing to stern of USS SENNET.

Figure 6. Passage through the Ross Sea ice pack.

Figure 7. Ross Sea ice pack, USS SENNET beset.

Figure 8. Ross Sea ice pack, USS Sennet beset.

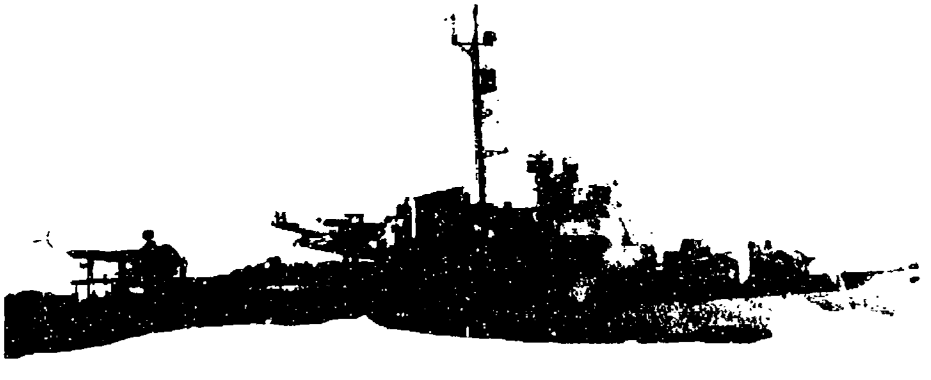


Figure 9. USCGC NORTHWIND, Ross Sea ice pack.

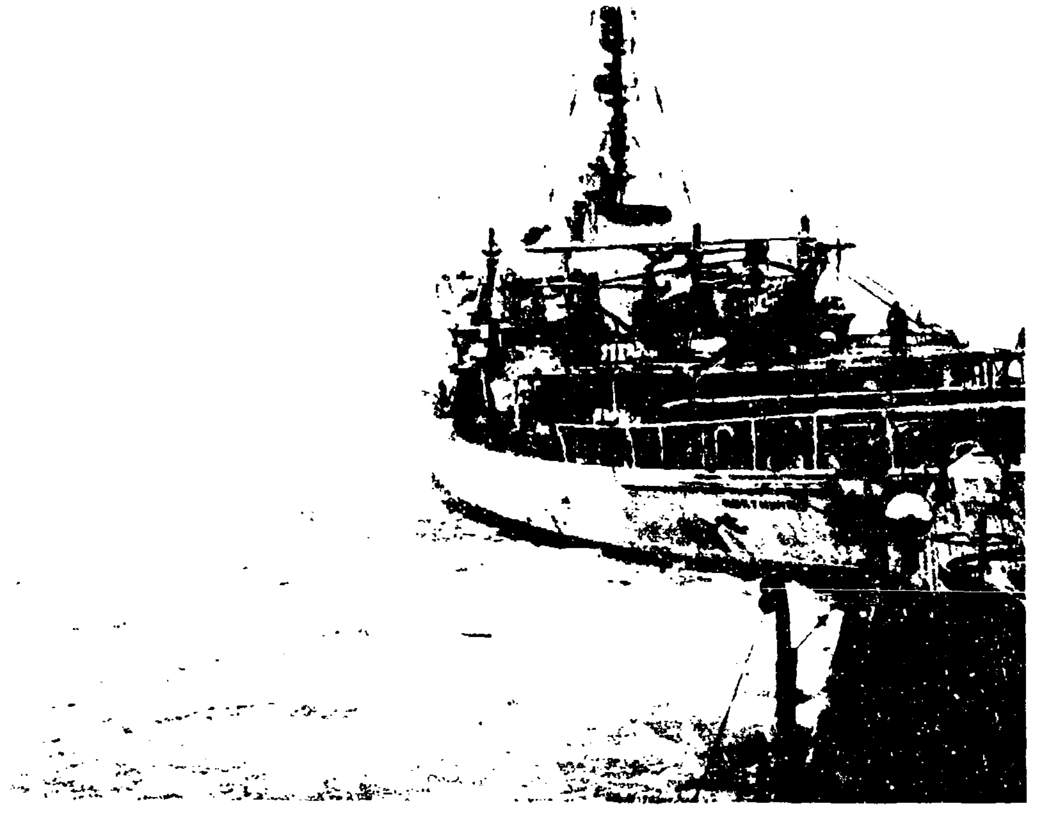


Figure 10. USS SENNET under tow by NORTHWIND, Ross Sea ice pack.

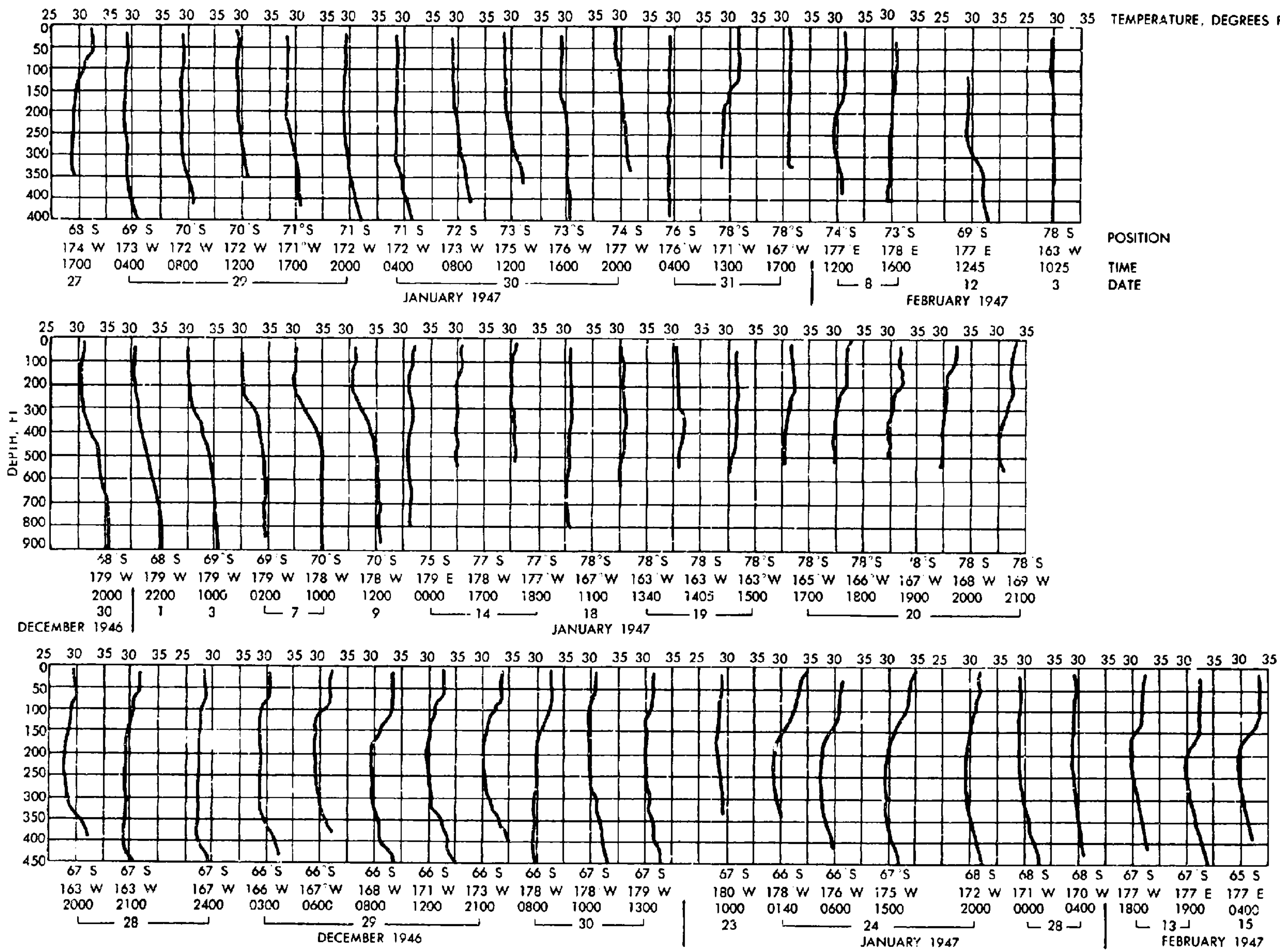
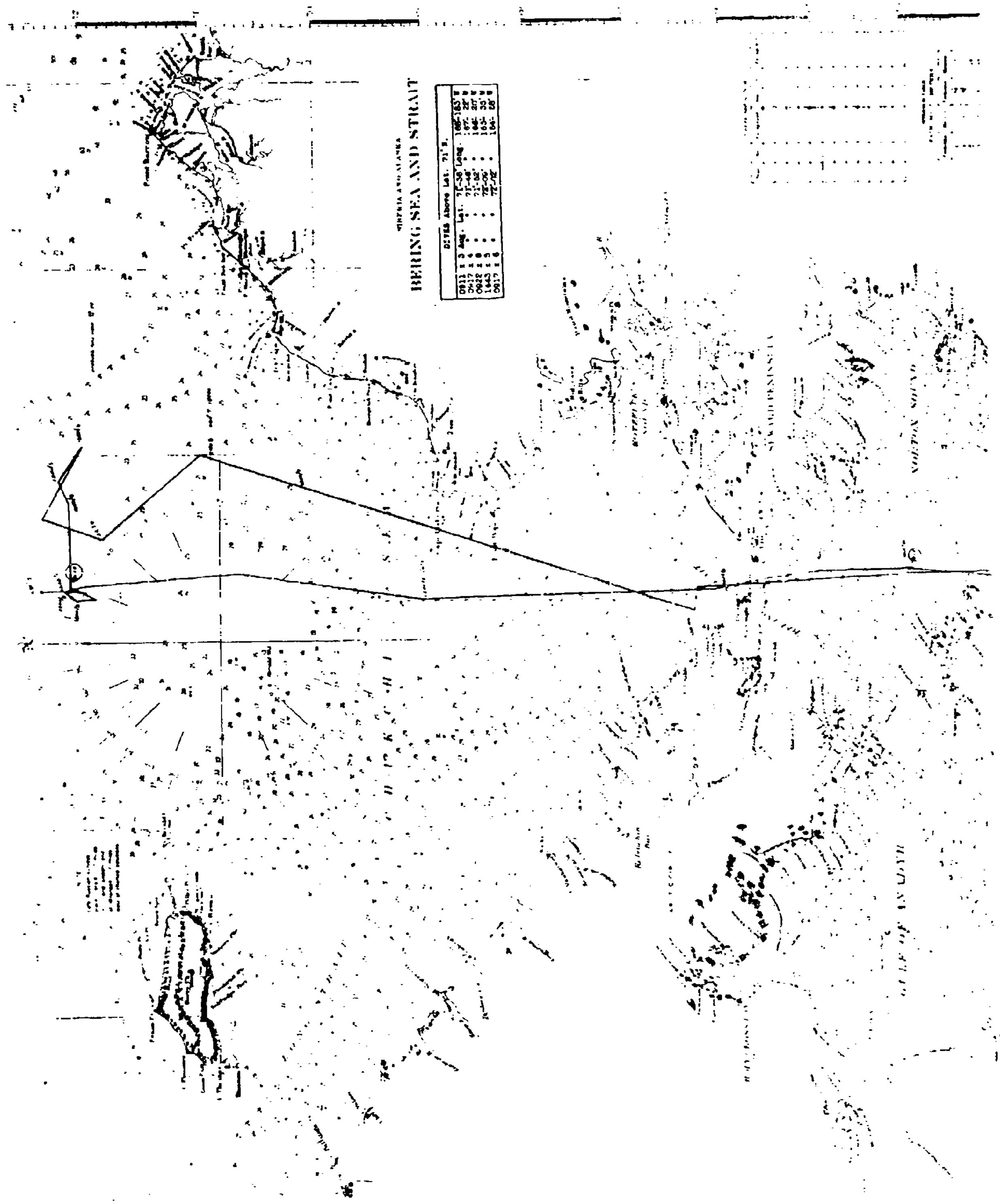


Figure 11. Typical bathythermograms, Ross Sea, USCGC NORTHWIND.


BERING SEA AND STRAIT
NORTON SOUND

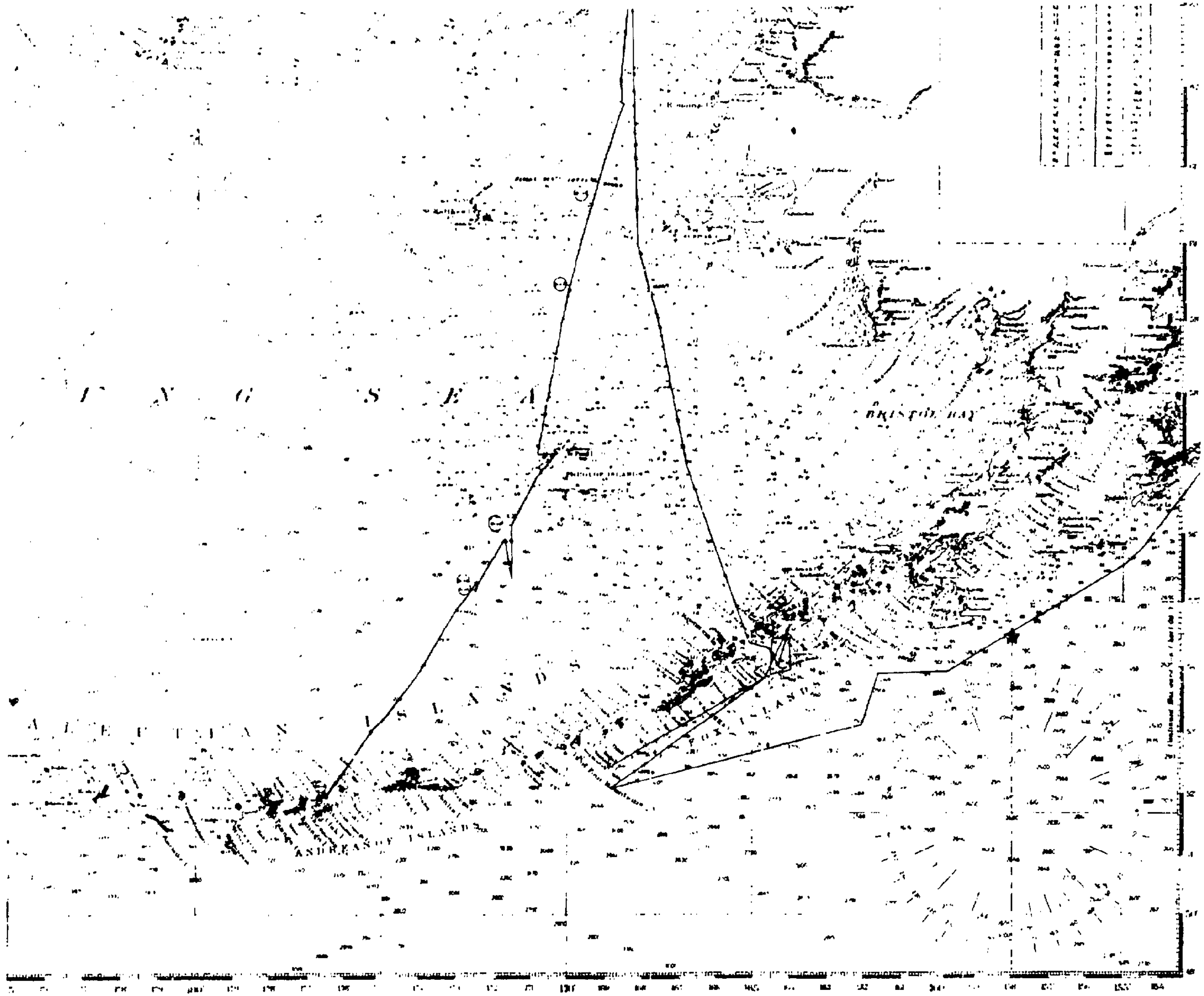


Figure 12. Track chart, USS BOARFISH, Chuckchi Sea, August 1947.

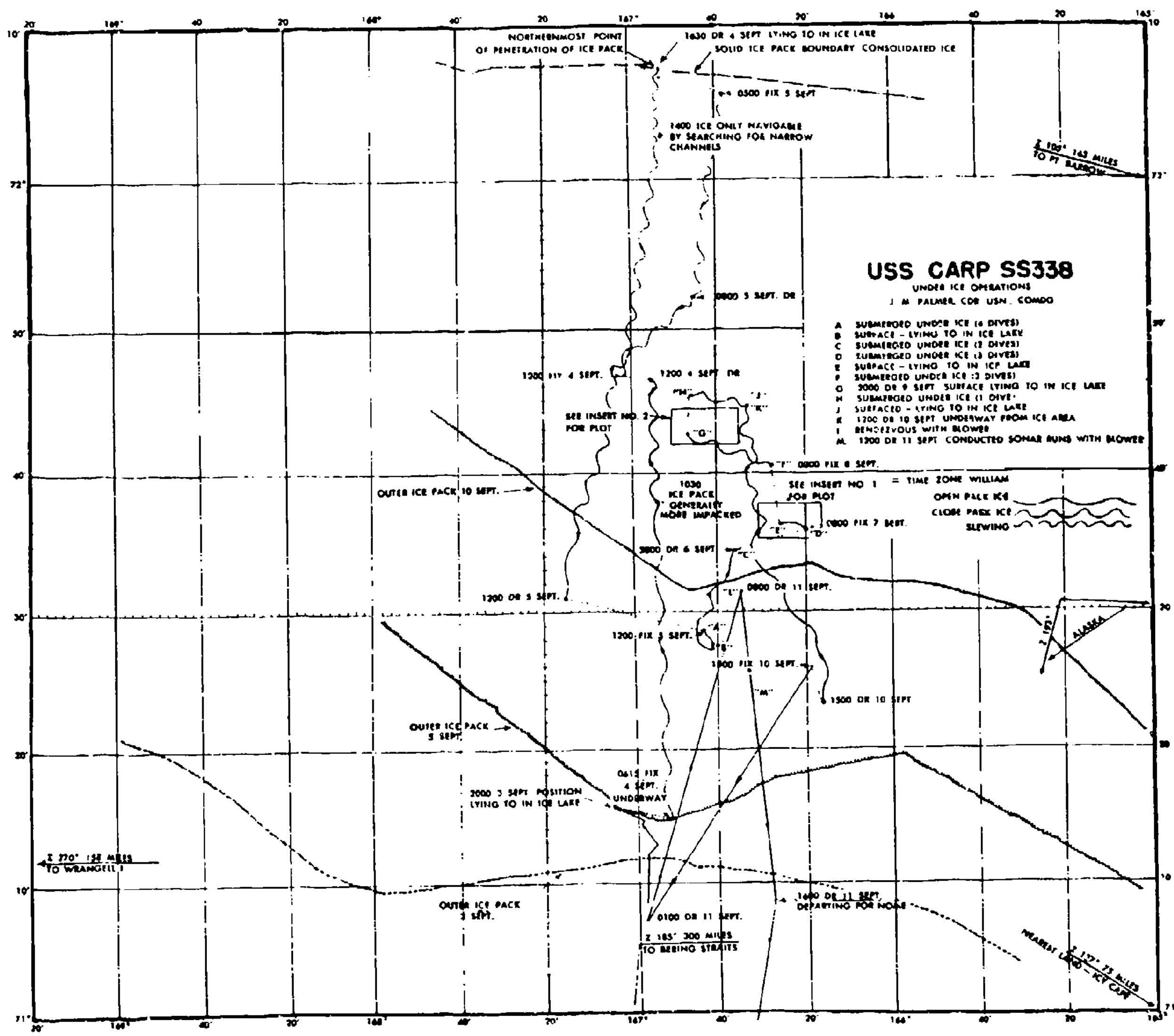


Figure 13. USS CARP under-ice operations.

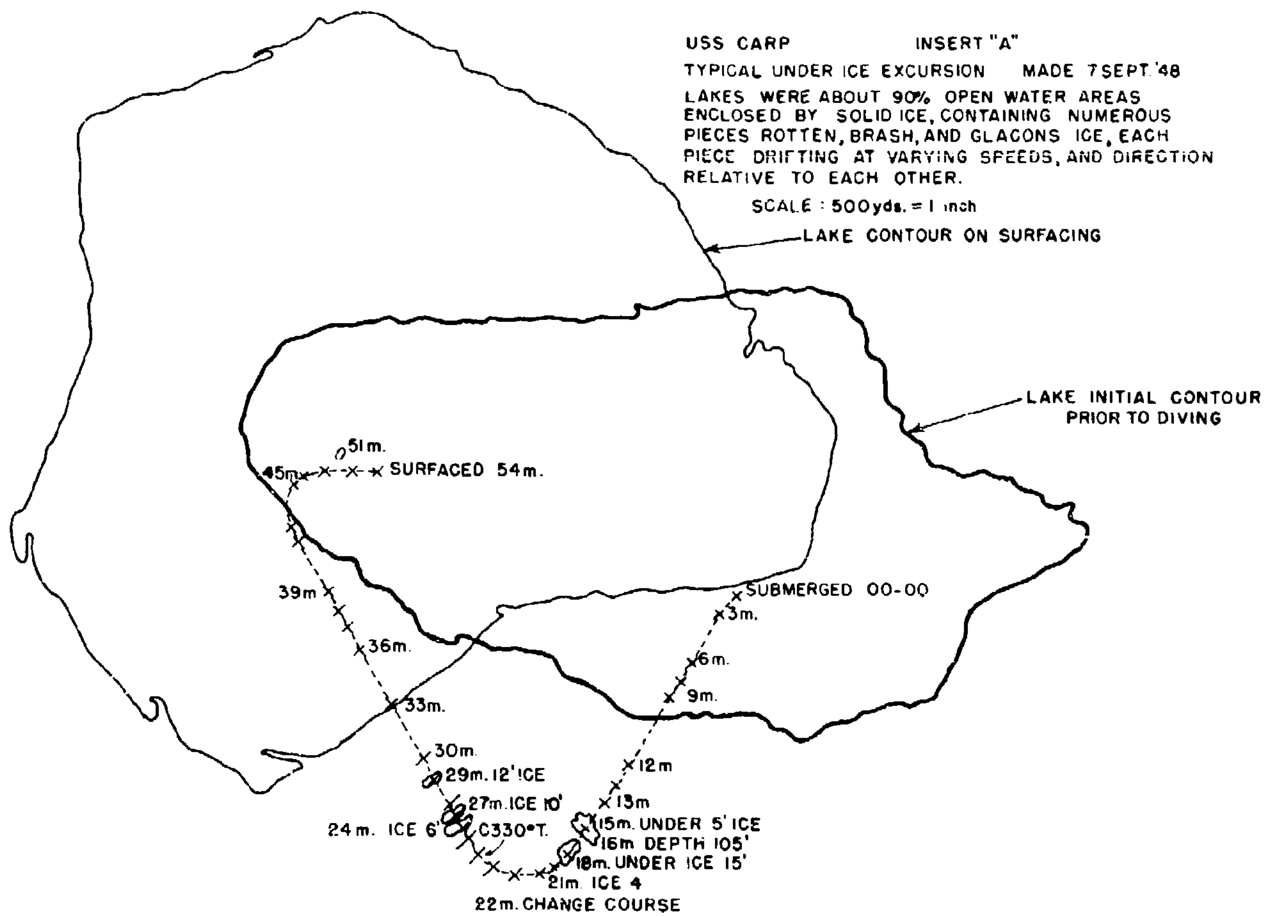


Figure 13-a. Typical under-ice excursion, USS CARP, 7 September 1948.

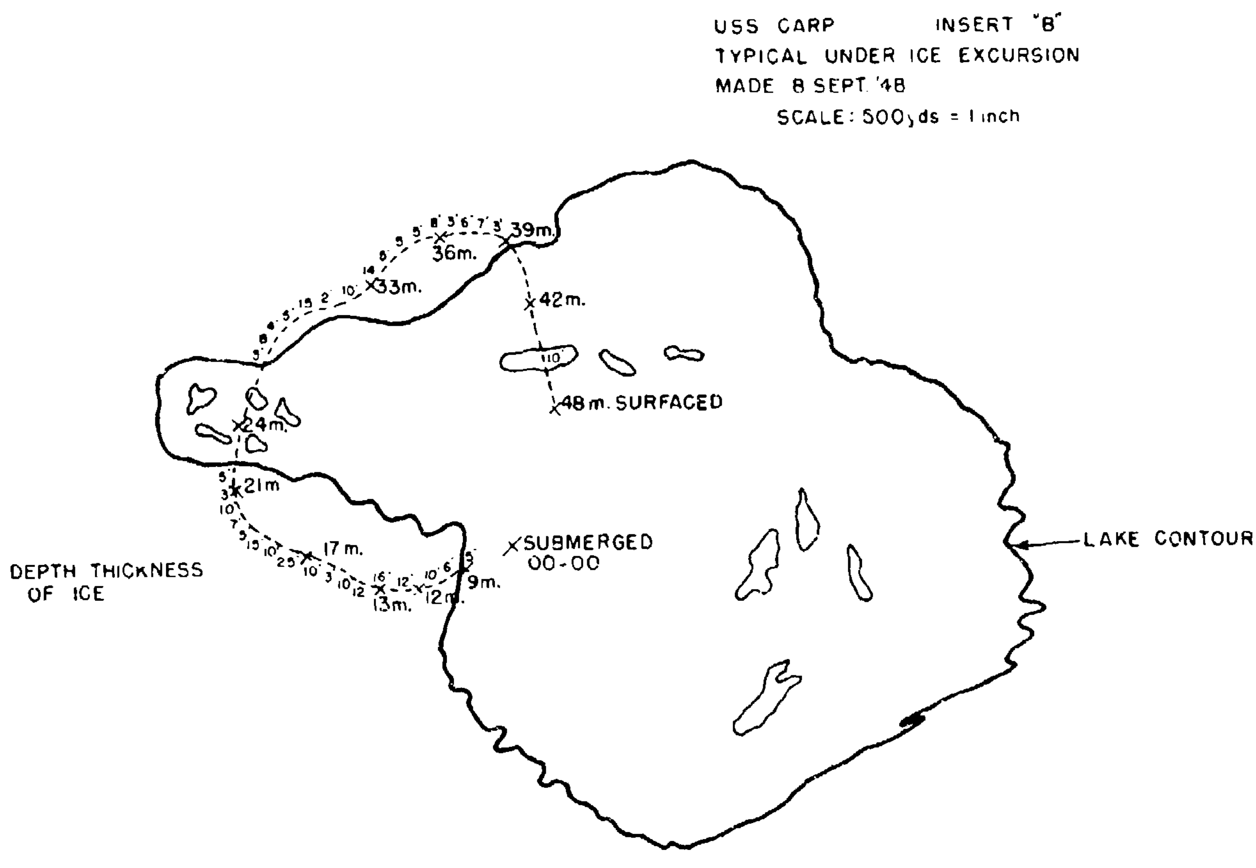


Figure 13-b. Typical under-ice excursion, USS CARP, 8 September 1948

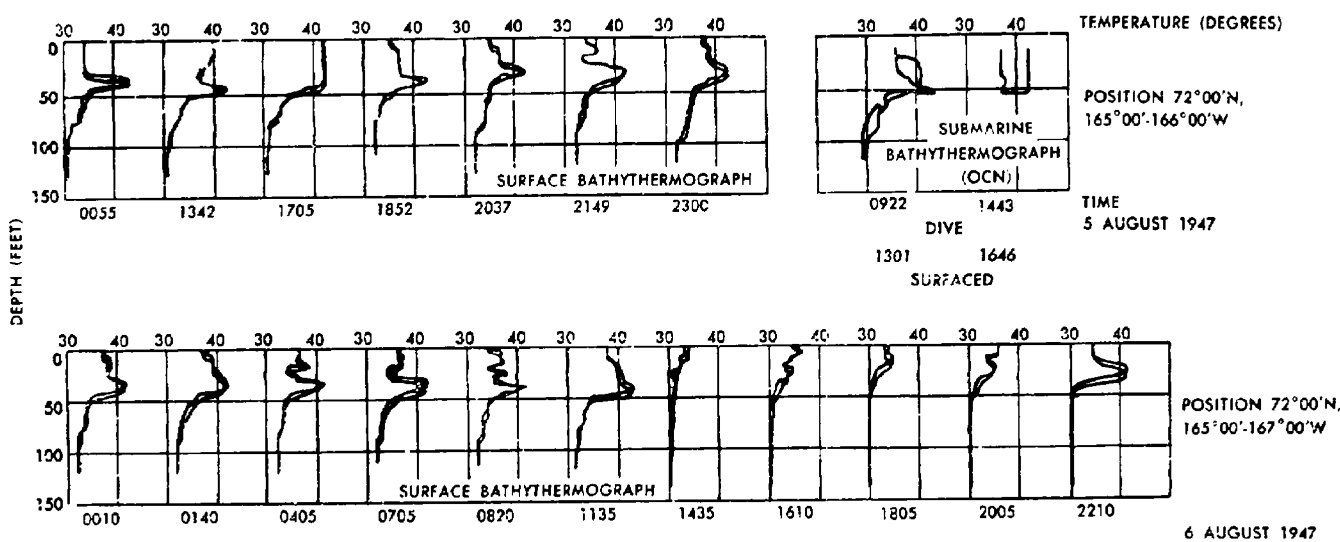


Figure 14. Bathythermograms, ice area, Chuckchi Sea, 5-6 August 1947, USS BOARFISH and USS CARP.

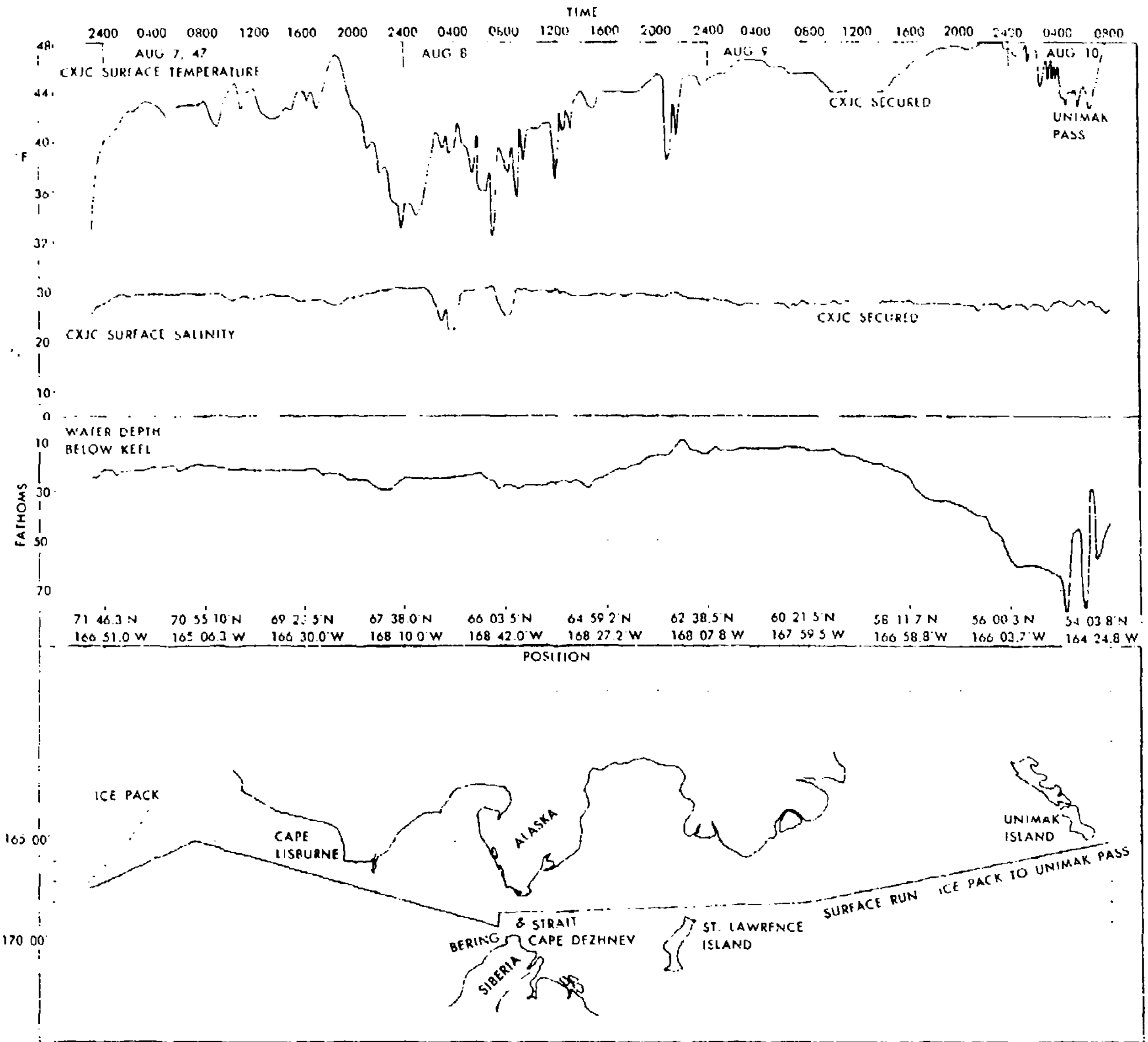


Figure 15. Surface temperature and salinity along track of USS BOARFISH, 8-9 August 1947.

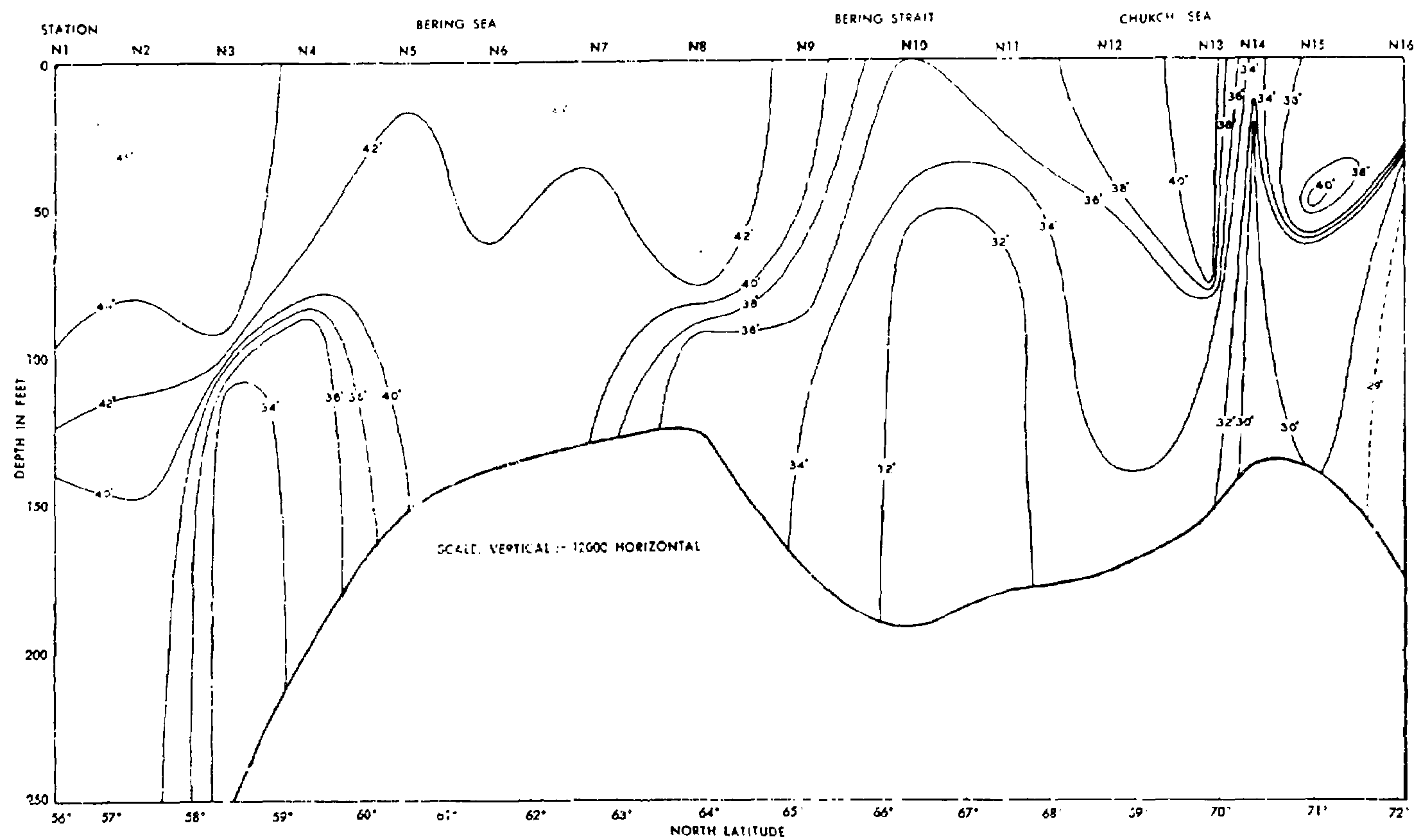


Figure 16. Temperature profile computed from oceanographic stations aboard the USS NEREUS.

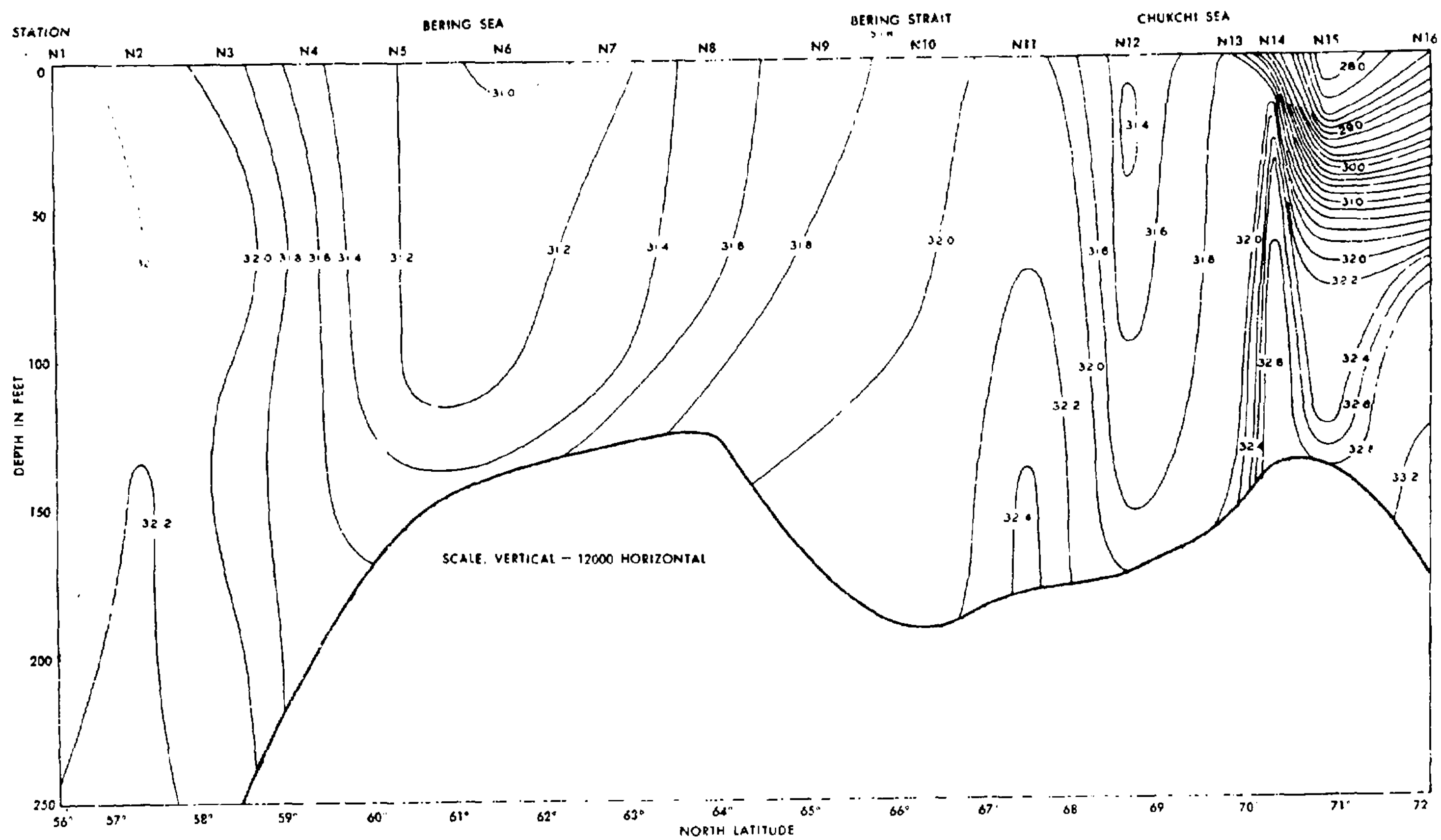


Figure 17. Salinity profile computed from oceanographic stations aboard the USS NEREUS.

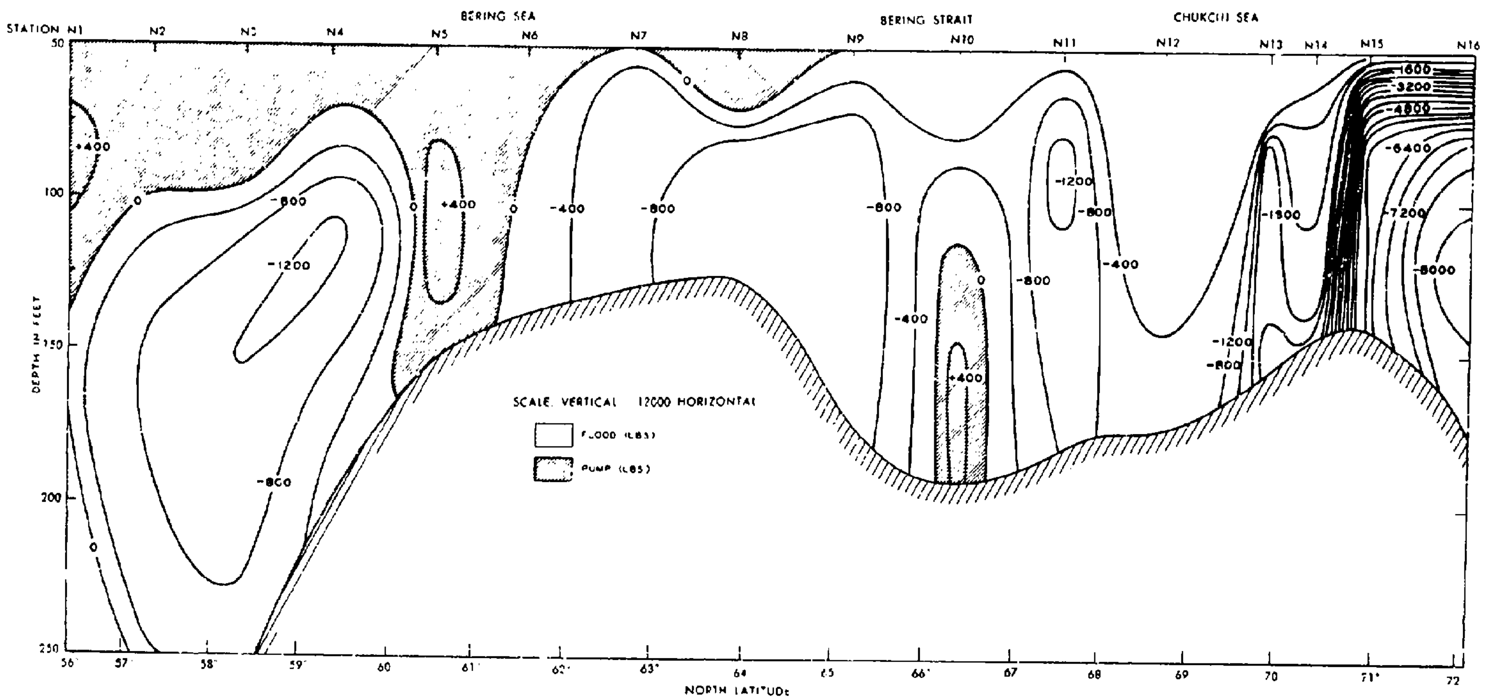


Figure 18-a. Computed buoyancy changes, 2100-ton submarine, section approximately along 170 meridian.

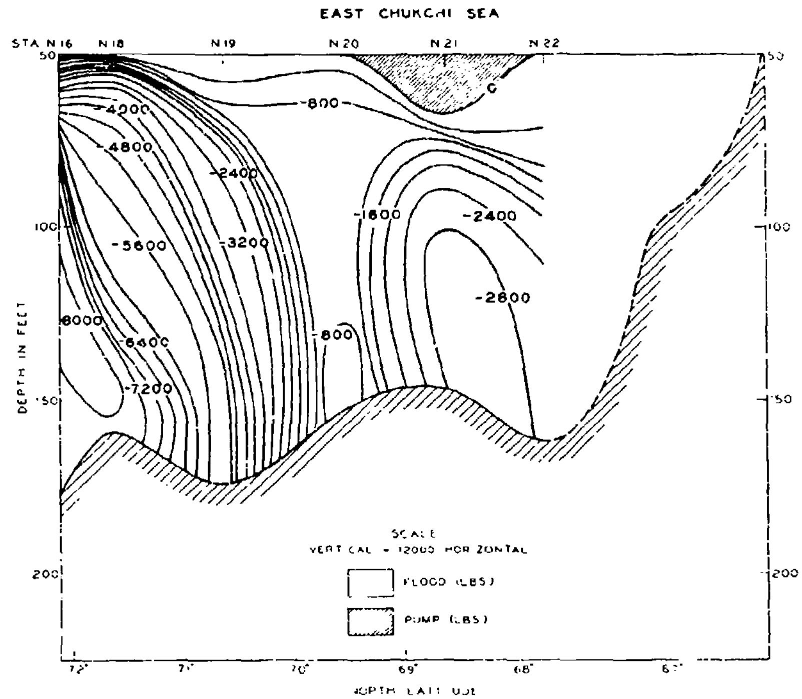


Figure 18-b. Computed buoyancy changes, 2100-ton submarine, section along approximate line from 72 N 170 W to Cape Lisburne, thence along shore to Kotzebue Sound.

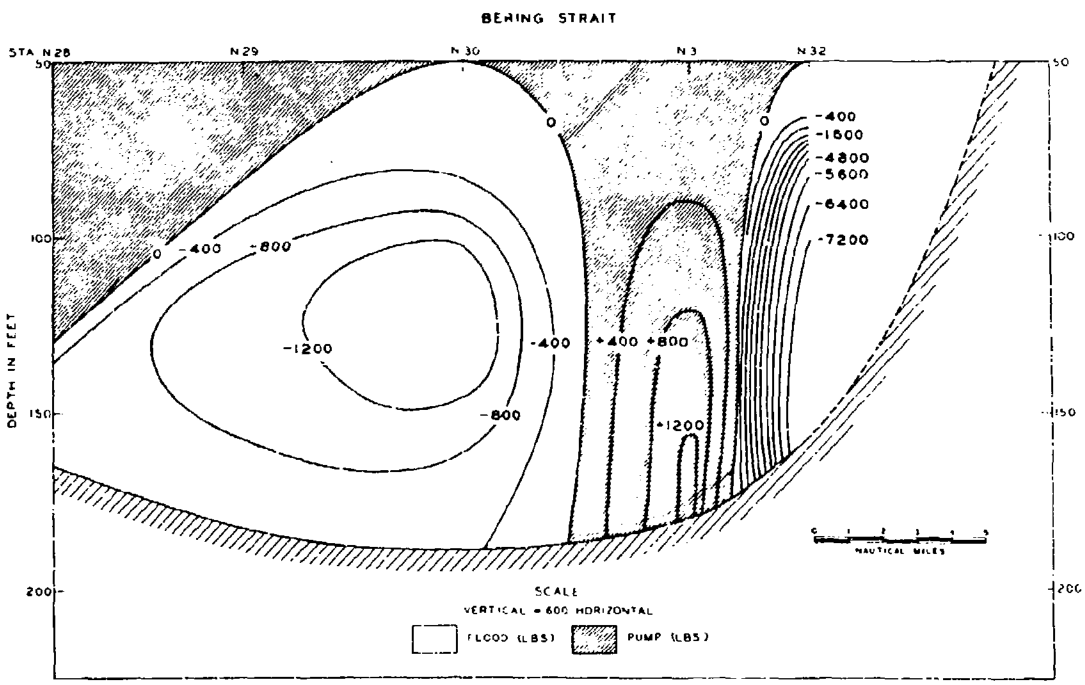


Figure 18-c. Computed buoyancy changes, 2100-ton submarine, section along course 300 T from Cape Prince of Wales.

and the diving procedure was very well planned and executed. The water density structure, though complex, was fully recognized, and proper buoyancy changes were anticipated. The amount of sea room was small because of the ice overhead and the shallow bottom (140 feet).

Vertical dives and ascents were made by control of safety tank. This tank is centrally located, so variations of its buoyancy do not disturb fore and aft trim. The venting of this tank produced a bubble screen which blanked out the sound gear. This difficulty can be prevented by inboard vents. The forward-aft trim was always very good, and it was interesting to note that second order shifts in trim were obtained by control of diving planes during ascents (e. g., forward planes thrown to extreme dive or rise to decrease surface normal to direction of motion). The procedure of stationary dives and ascents as concisely described by Comdr. Palmer[6] is quoted below:

"Normal diving and surface procedure required revision while operating in the arctic ice-field as vertical ascents and descents were almost always mandatory. Diving procedure varied from that normally used in that negative tank was only partially flooded (12,000 pounds) to prevent an excessive down angle. Submergence rate was controlled by the rate of blowing negative tank to its normal trim level of 6,000 pounds. In the case of the bubble, it was noticed by starting to blow safety slowly at 50 feet, the longitudinal stability was of sufficient force to prevent seesawing and the bubble could be controlled if the fore and aft trim was within limits of 1,000 pounds. At times a small bubble in safety tank was required to stop the descent so as to obtain a trim at the ordered depth. For ascending vertically, enough water was blown from safety tank to obtain a positive buoyancy of about 4,000 pounds. Since there was no means for blowing exact amounts from safety tank it was often necessary to reduce the rate of ascent by partially venting safety tank. The bubble was controlled by using the planes to increase or reduce the resistance to ascent on either the bow or the stern, as applied. The more rapid the rate of ascent, the more effective was this method of control of the bubble. The point at which safety was vented to stop at the desired depth depended upon the rate of ascent and depth of layer present. In ascending into layers of different density than the one in which the hovering trim had been obtained, while on the way up, enough water was pumped from or flooded into auxiliaries to give about 3,000 pounds negative buoyancy at the new depth. As soon as the rate of ascent was checked, this excess water was removed and a hovering trim was attained. The chief disadvantage in using safety tank was the necessary venting which blanked out the sonar gear. The time of venting safety and the time of needing information on the ice disposition nearly always coincided. A large inboard vent on safety tank or a small amidship tank of about 10,000 pounds located at the center of buoyancy which could be blown or vented inboard or in which the amount of water could be varied by a hydraulically operated water displacing piston would eliminate this condition by providing a more flexible means of depth control."

The BOARFISH and the CARP were equipped with a modified CXJC-1 unit, which measured the temperature and salinity and computed the expected ballast changes to maintain neutral buoyancy. The equipment was modified to record separately salinity and temperature and proved valuable in giving a continual recording of these two parameters for the oceanographic study. The errors in these records compared to point checks on bucket samples with thermometer and hydrometer appear to be within expected allowances (2° F. and 0.25 $^0/_{00}$). The ballast change indicated by the buoyancy recorder did not always fall within the allowable error of the value computed from the temperature-salinity data. Very gross discrepancies were observed during both

patrols between predicted and actual ballast changes. Operationally, salinity-temperature recorders (CXJC, OCN) did not contribute to the *prediction* of ballast changes but to the qualitative *explanation* of changes that the diving officer found necessary. Often, the explanation was only that the density structure had changed. The records and observed ballast changes have not been thoroughly studied, nor has the equipment been given a laboratory check and calibration, which it is hoped will resolve the discrepancies. This work will be covered in a later report.

A bathythermogram was taken by lowering a surface-ship type BT overside prior to dives in the ice areas. The important layers were noted (usually bottom, and periscope depths) and water samples then taken in each layer by a Nansen bottle cast. These data gave a fair expectation of the dive. Since many observations were taken from the deck a convenient boom was rigged for overside lowerings, and is shown in figure 19. The boom folded into sections for stowage in the forward torpedo room.

The intense temperature layers, of course, provide many opportunities for "floats." In the Bering Strait, on 30 July 1947, the BOARFISH readily floated on a stable layer at periscope depth. The surface layer, 40.8°F., was well mixed to a depth of about 58 feet with a steep temperature gradient to 36.2°F. in the next 2 feet of depth. The change in salinity was from 28.5 $^0/_{00}$ to 29.8 $^0/_{00}$. The vessel appeared to vary about 2 feet in depth every 4 or 5 minutes; however, insufficient data were taken to judge any presence of internal waves. A number of "floats" were made inside the fringe of the pack ice. A dive at 40 feet was conducted 3 August for 5 miles into the pack ice. Advantage was taken of a temperature layer at the 40-foot depth, and numerous floats were made for comparisons of QLA contacts with ice observations by periscope.

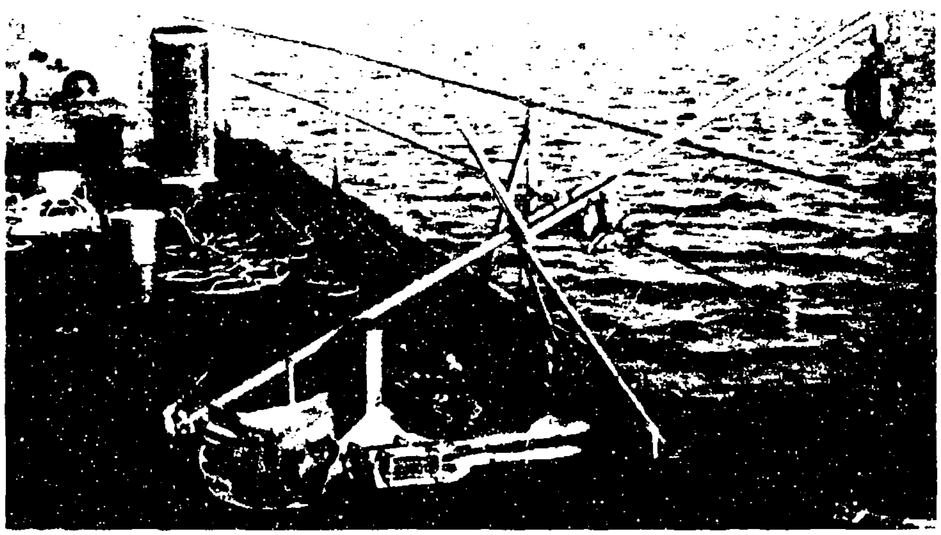


Figure 19. Boom rig, USS CARP.

During the summer, the surface salinity is very variable and often falls to low values (less than 15 $^0/_{00}$) because of the rapid melting of old ice. Hence, the density of the surface layer has large variations and localized, unusually low, values. For example, the CXJC record for salinity, temperature and calculated density (fig. 20) was taken during a surface run into scattered ice by the BOARFISH. The lower limit of the Esterline-Angus recorder for salinity was set at 15 $^0/_{00}$. The observed value was found to fall below this setting in numerous patches of water some 16 miles north of the ice limit. An estimate of the size of the low-density patches, or of the distance between patches, cannot be made from the record since the course and speed of the vessel were much too variable.

An attempt was made to record continually buoyancy parameters on the CARP during the stationary dives and ascents. The CXJC equipment provided continuous observations of water temperature, salinity, and conductivity. Microtorque potentiometers were mounted on diving plane indicators, pressure gauge, and liquidometers in order to measure changes in buoyancy control (fig. 21). The hull angle was measured by a pendulum device mounted in the forward room (fig. 22). The record was taken on a six-channel Brush recorder (ink on paper), controlled by a programming switch (fig. 23). The recorded parameters and program times are listed in Table III. The choice of programs was not judicious since the importance of the safety tank record was not realized until the stationary diving procedure was initiated. A study of the recordings is in progress; however, results are not available for this report.

TABLE III. BUOYANCY PARAMETERS RECORDED ABOARD USS CARP

Parameter	Measuring Method	Program Time During Each Minute (seconds)
Water temperature	CXJC	60
Salinity	CXJC	45
Specific conductance	CXJC	15
Hull angle	Damped pendulum	45
Depth	Pressure gauge	15
Bow plane angle	Plane indicator	45
Stern plane angle	Plane indicator	45
Speed	Pit log indicator	15
Rudder angle	Rudder indicator	15
After trim	Trim tank liquidometer	15
Ballast — Auxiliary No. 1	Tank liquidometer	15
Ballast — Auxiliary No. 2	Tank liquidometer	15
Ballast — Safety Tank	Tank liquidometer	15

Ice Conditions

The ice encountered in the Chukchi Sea was the fringe, or pack ice, of the arctic pack. The pieces were mostly flat glacons interspersed among much brash and rotten ice; some were heaped, showing origin from pressure ridges of the arctic pack. Typical conditions are illustrated in figures 24 through 34.

Considerable quantities of mud were imbedded in many glacons and floes, which indicated the ice had originated from fast ice. Ice which is grounded along the Alaskan and Siberian Coasts during winter and spring picks up mud on its lower surface. This mud works up through the ice during subsequent summers and winters, since melting

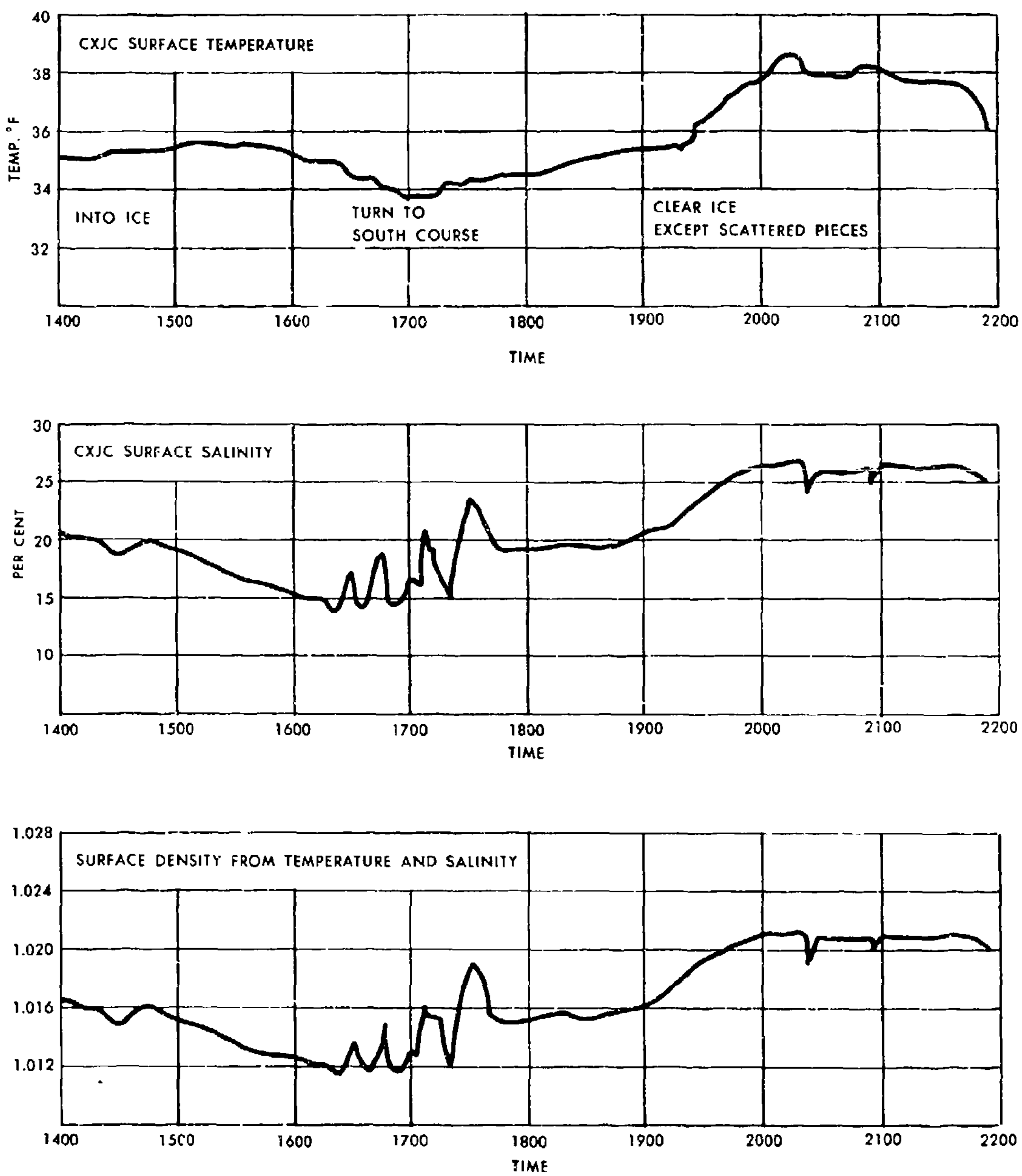


Figure 20. CXJC record of surface temperature and salinity, and calculated density, taken during BOARFISH run into scattered ice.

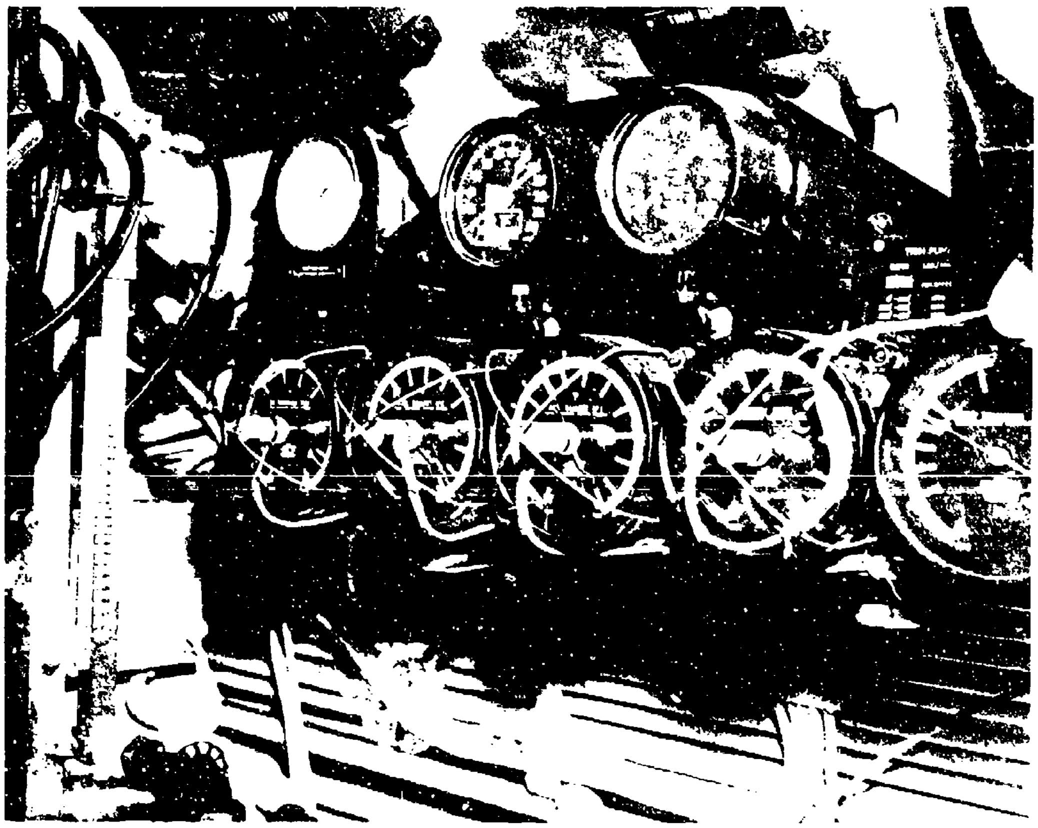


Figure 21. Microtorque potentiometers mounted on ballast liquidometers, USS CARP.

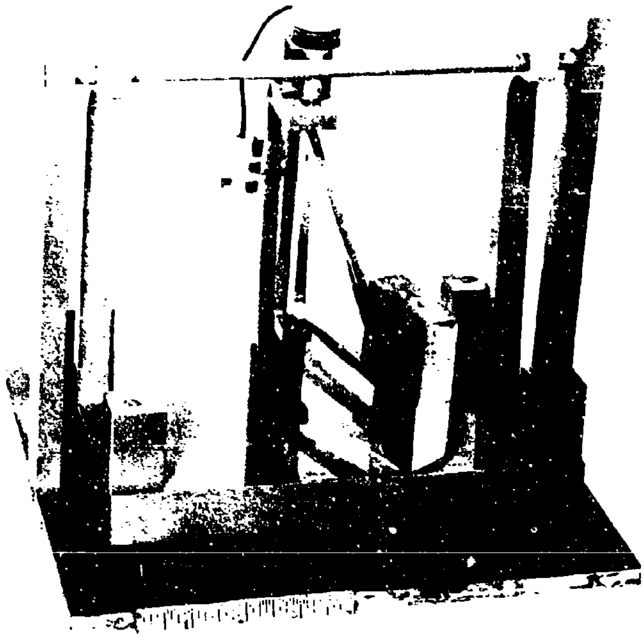


Figure 22. Hull angle indicator, USS CARP.

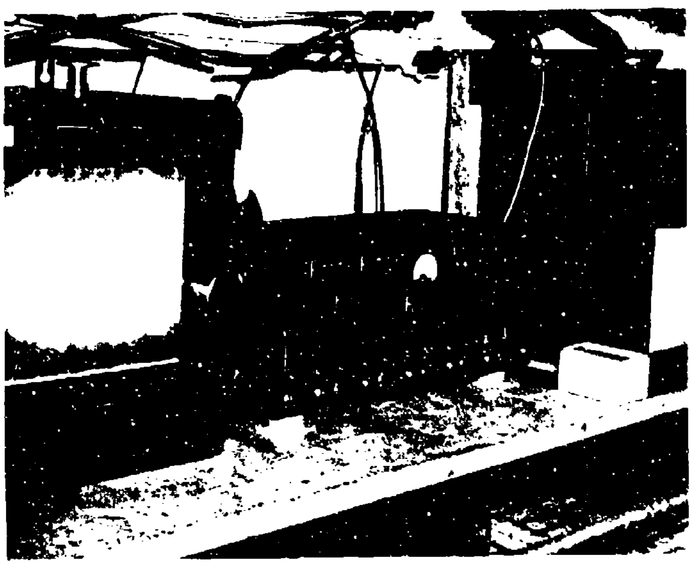


Figure 23. Brush recorder, bridge circuits, and CXJC unit, forward torpedo room, USS CARP.

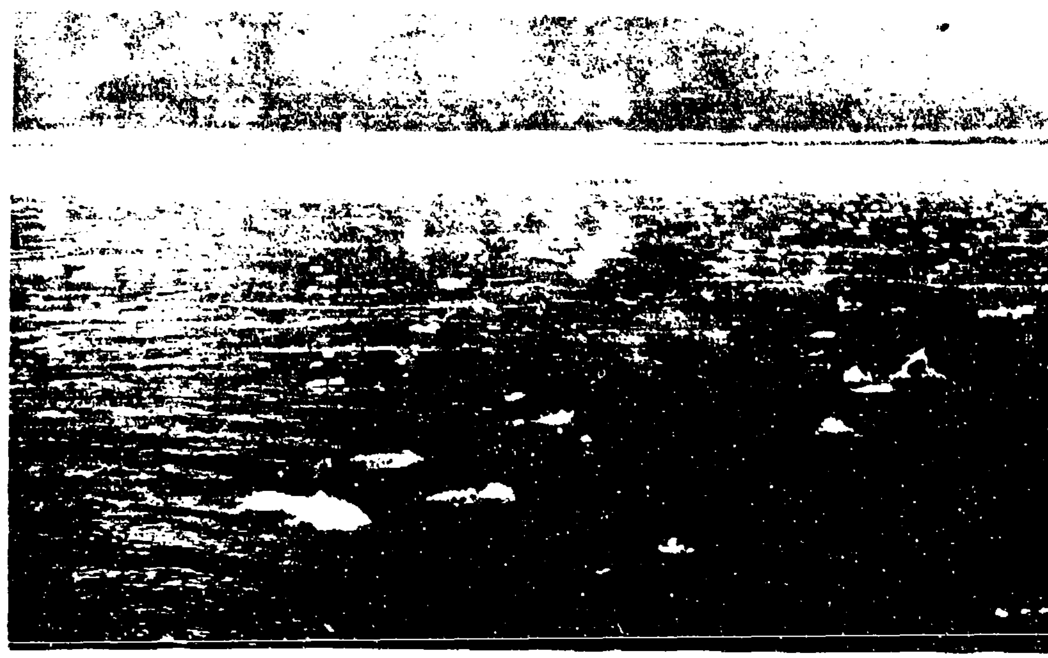


Figure 24. Scattered brash, surface sonar frustration, USS BOARFISH.

Figure 25. Brash ice, USS BOARFISH, 1947.

Figure 26. Debris ice, considerable sediment entrapped, USS BOARFISH, 1947.

Figure 27. Glacons, USS BOARFISH, 1947.

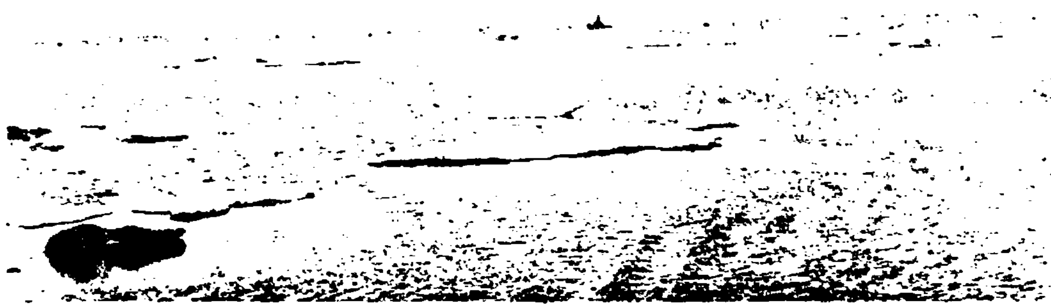


Figure 28. Brash ice, USS CHUBB in background.

Figure 29. Brash ice, USS CARP, 1948.

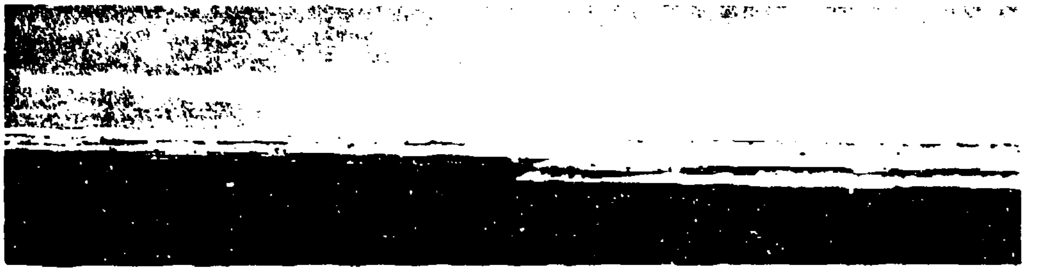


Figure 30. Ice floe, USS CARP, 1948.

Figure 31. Ice floe, USS CARP, 1948.

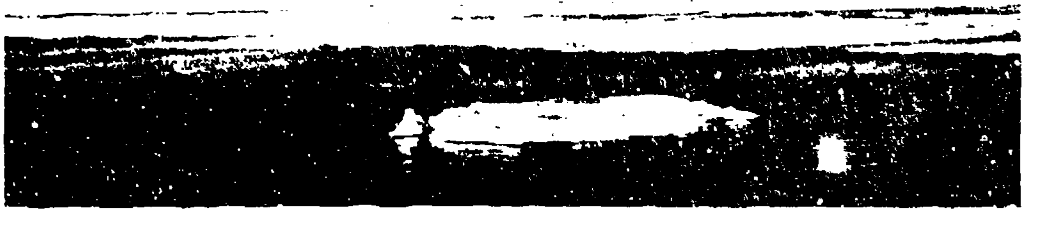


Figure 32. Ice floes forming lakes in which CARP dived, 1948.

Figure 33. Ice floes, USS CARP, 1948.

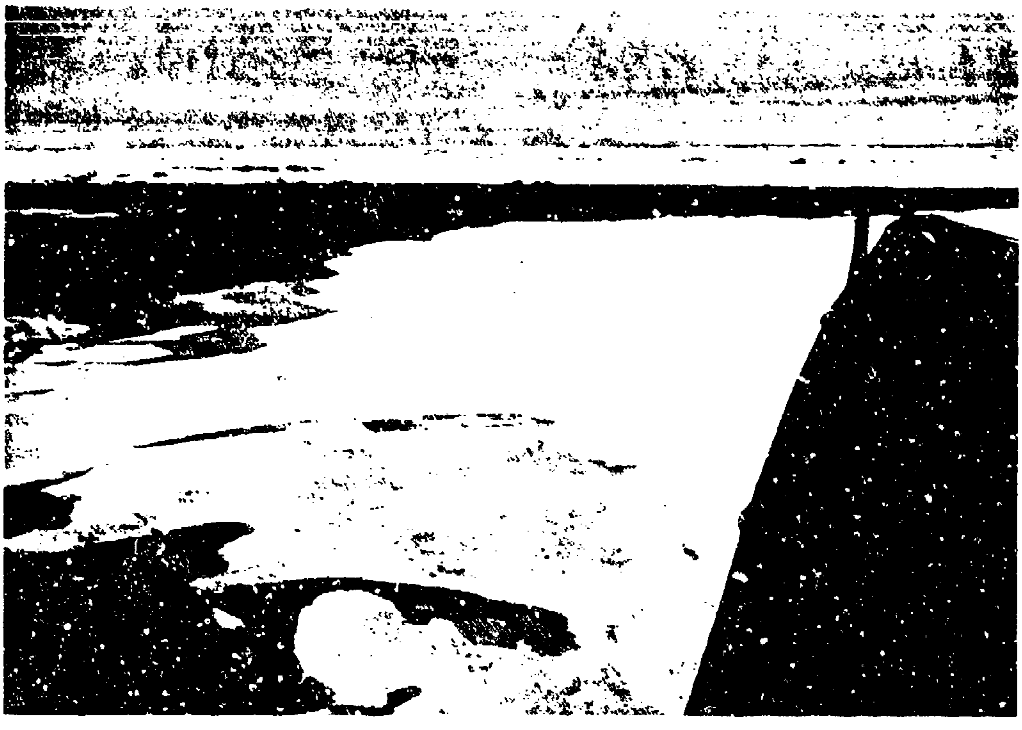


Figure 34. Ice floe, USS CARP, 1948.

takes place on the upper surface during summer and new ice builds on the lower surface during winter. The mud is a fine silt which, when the ice melts, is contributed to the flat, delta-like bottom of the Chukchi Sea. The surface run of the CARP carried through 55 miles of loose pack ice to the edge of the arctic pack. The vertical dives and under-ice operations were conducted in the leads and lakes illustrated in figures 29 through 41. Occasionally, it was necessary to break through ice when a lead was not available. The techniques at flooding down aft and riding up on the ice, which had been successfully used by the SENNET in the Ross Sea, were applied with good success. One breakthrough is shown in figures 35 to 38; the ice crack was generated by ramming.

Aircraft of the VPAL Squadron 20 conducted aerial reconnaissance of ice in the vicinity of the CARP's operations and north to the arctic pack. A copy of the aerial ice plot is shown in figure 39. During the reconnaissance flight of 5 September 1948, vertical overlapping photographs were taken; examples are shown in figures 40 and 41. The area which was photographed and the flight track is indicated on figure 39. It is pertinent to note that the CARP operated in the areas covered by this reconnaissance, 71°10′ to 72°8′N, 166-167°W.

Figure 35. Crack through floe formed when USS CARP rammed pack ice.

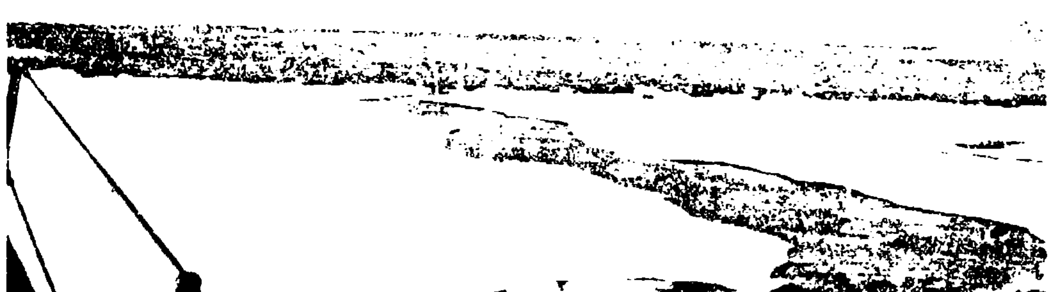


Figure 36. Opening of crack in figure 35.

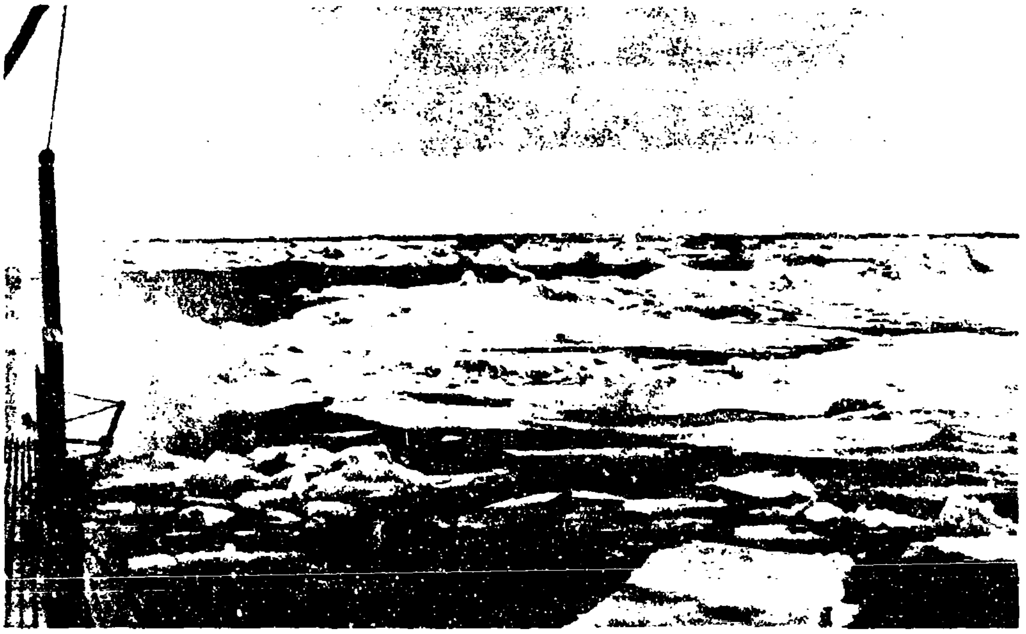


Figure 37. USS CARP, 1948.

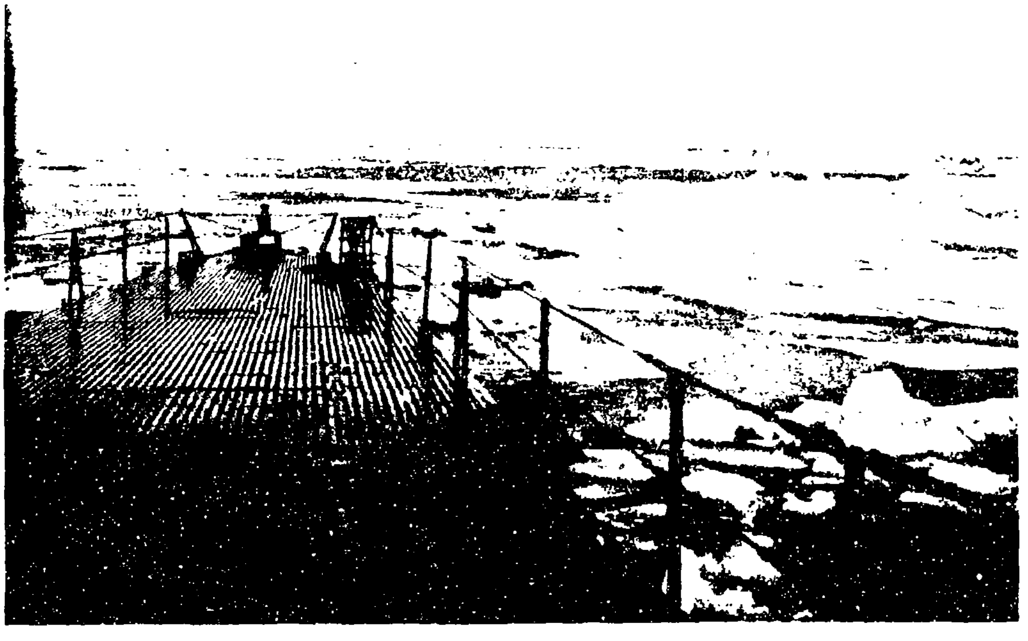


Figure 38. USS CARP, 1948.

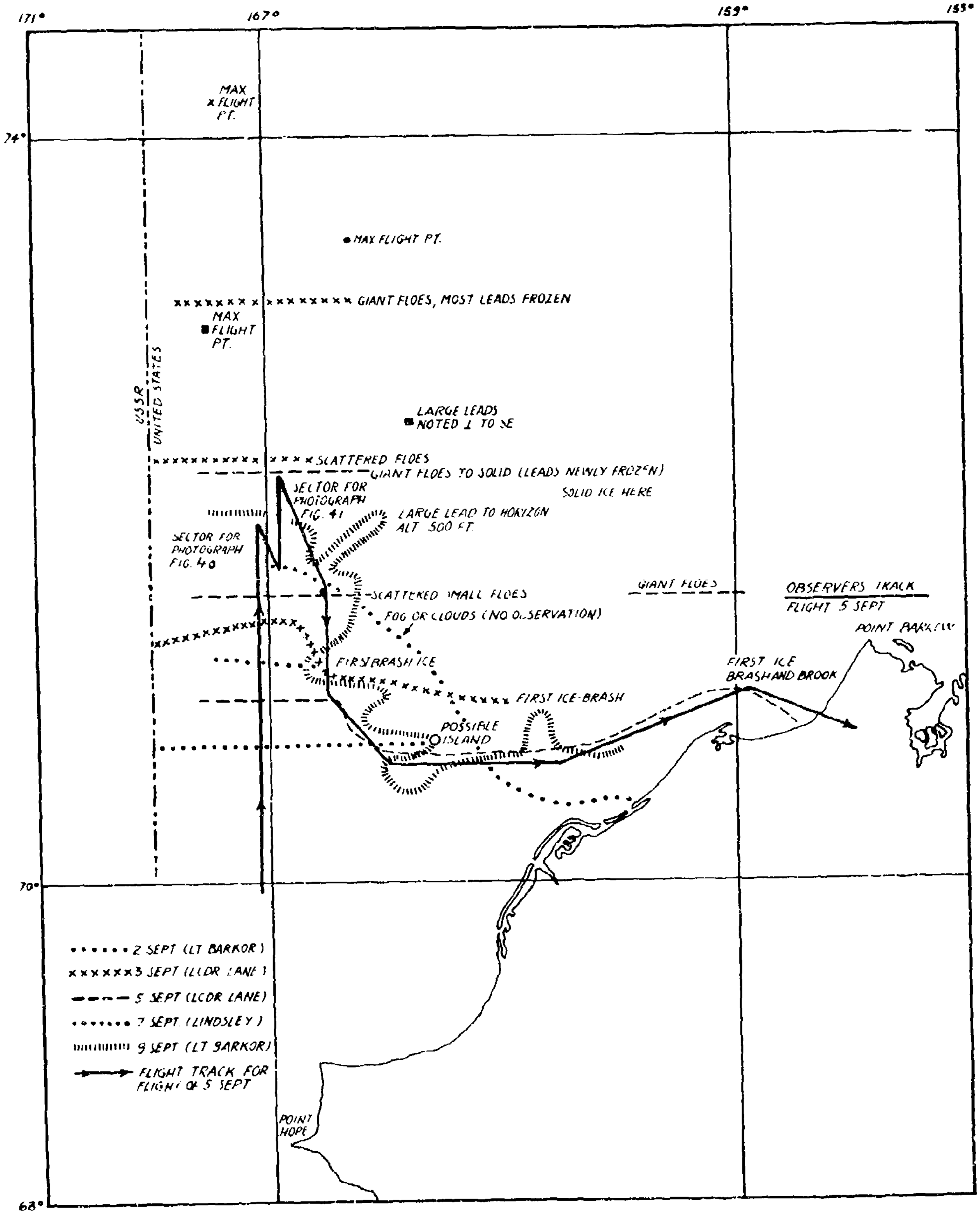


Figure 39. Flight chart, aerial reconnaissance of VPAL Squadron 20.

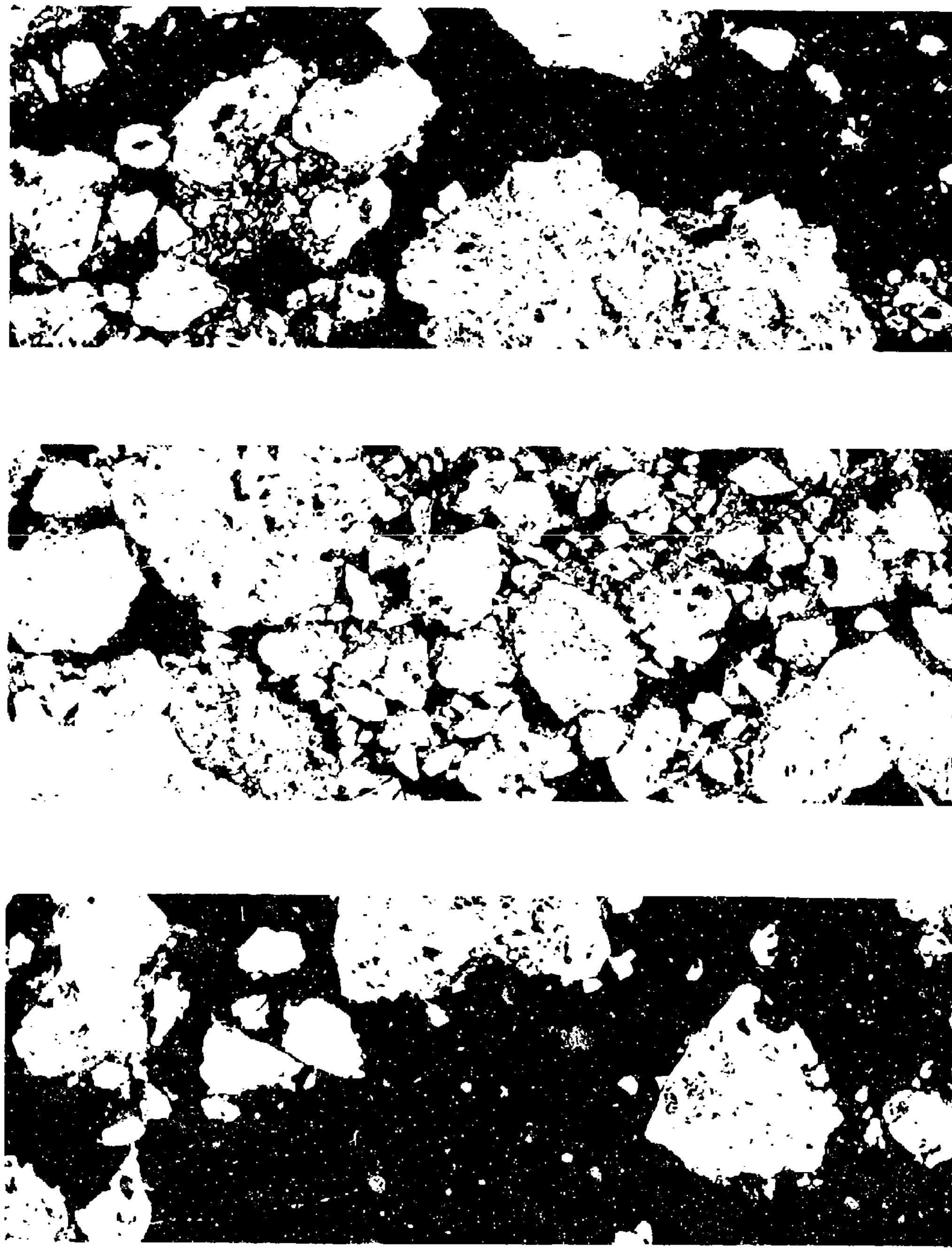


Figure 40. Aerial photographs, sector A, taken during reconnaissance flight, 5 September -- height, 4500 ft; length of sector approximately one mile.

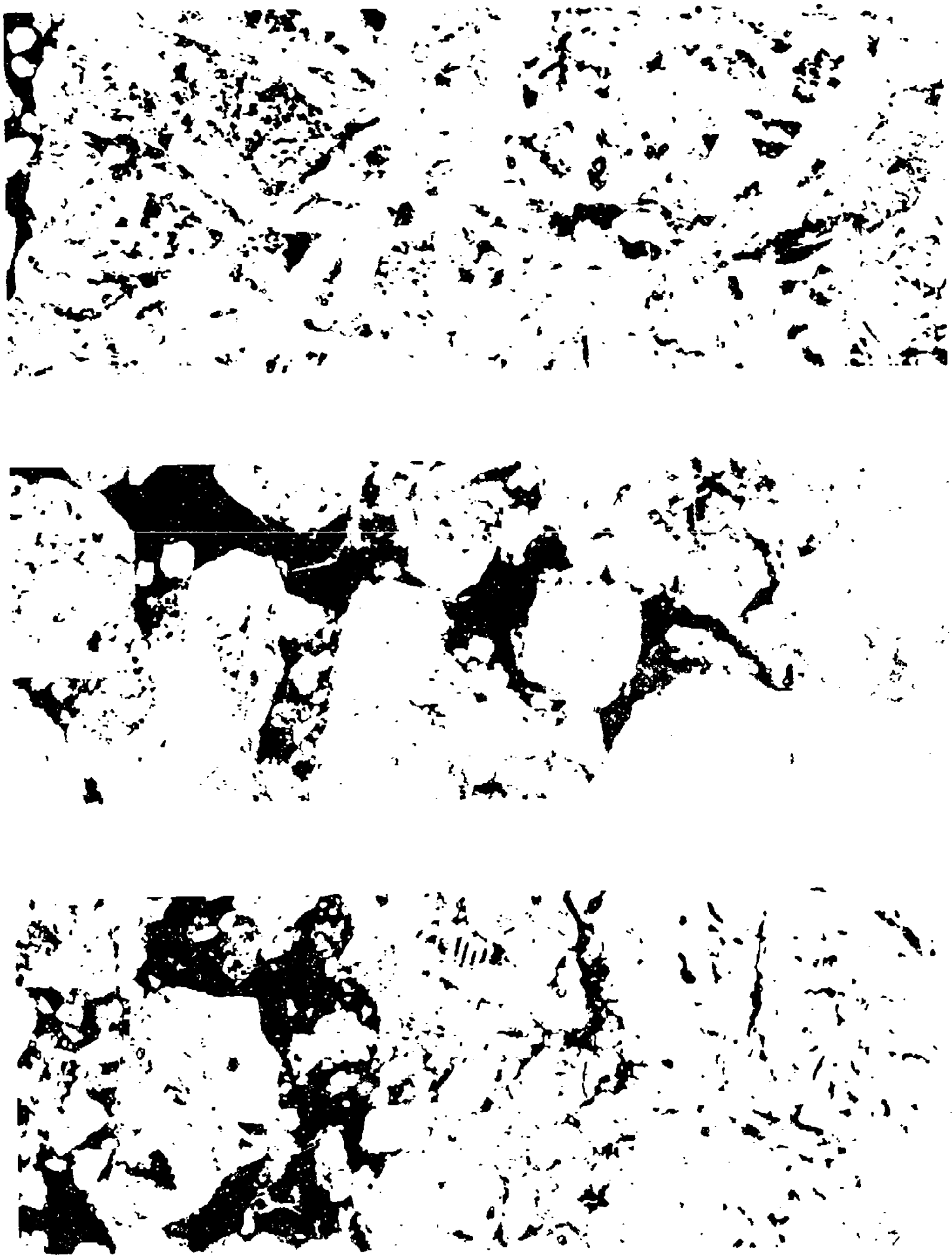


Figure 41. Aerial photographs, sector B, taken during reconnaissance flight, 5 September – height, 4500 ft; length of sector approximately one mile.

Sonar and Under-Ice Navigation

The BOARFISH was successful in three extended dives under the pack ice. Rear Admiral A. R. McCann, Captain L. C. Chappel, and Captain D. C. White were aboard the BOARFISH for the initial dive on 1 August 1947.

The QLA scanning sonar was used to navigate under the ice. The PPI presentation was shown to be the expected prerequisite for under-ice navigation by sonar. The type NK portable fathometer (Submarine Signal Co. 808B, 200 foot/fathom, sectored scale) mounted on the deck recorded the distance of the deck below the ice, and, in addition, provided information on the acoustical properties of sea ice. The various sonar equipments and associated instruments which were carried by the BOARFISH are listed in Table IV. Only minor maintenance repairs were made to any of the equipments, though one embarrassing trouble occurred during the initial under-ice dive when the key slipped out of the training shaft keyway of the topside QLA sound head and made it inoperative. Equipments installed on the CARP are listed in Table V and are shown in figure 42.

Figure 42. Sonar equipment, USS CARP.

TABLE IV. EQUIPMENTS ABOARD USS BOARFISH

Equipment Purpose	Type Model	Serial	Location of Controls	Location of Sea Units	Remarks
Supersonic listening and echo ranging	WCA-2 QC/QB	44	Conning	Port-bottomside	Wiring shifted from conventional system to drive JK side of QC/JK combination as QB unit
Fathometer	NGA	27	Control	Keel	
Scanning sonar	QLA-1	28	Conning	2 transducers—starboard, bottom and topside	One system connected to either head by patch cords
Echo sounder for depth below ice	NK		F.T.R.	Topside, starboard	
Sonic listening	JT, JP-2	29, 85	F.T.R.	Topside, port	
Bathythermograph	OCN		Conn. & Cont.	Sheers	
Buoyancy control and sonar ranges (including salinity)	CXJC-1	X5	Conn. & Cont.	Bow, just above tubes	Unit modified to give continuous separate recordings of temp. and salinity on 2 Esterline-Angus milliometers
Measure short time horizontal thermal structure	Thermopile		F.T.R.	Bow, just above tubes	Laboratory equipment, Esterline-Angus recorder
Record aural indications on QLA	Sound Mirror rec. Brush Dev. Co.				
Sound monitors 100 to 20,000 cps. Monitor for shipboard equipment	OAY OCP			Overside while lying to Overside while lying to	Over-all measurement ambient noise level
Surface-ship BT. Measure vertical thermal structure				Hand-towed overside while lying to	Very useful for measuring profiles before diving
Evaluation of sonar conditions	24-inch triplanes			Suspended from Dan Buoy	Used for qualitative evaluation of sonar conditions, Adak cruise, Bering Sea

TABLE V. EQUIPMENTS ABOARD USS CARY

Equipment Purpose	Type Model	Location of Controls	Location of Sea Unit
Supersonic listening and echo ranging	WFA	Conning or F.T.R.	Multiple projector topside, starboard QB projector bottomside, starboard
Scanning sonar	QLA-1	Conning	Topside — port
Topside fathometer	808J(NK)	Forward room	Topside, just aft of capstan
Zenith scanner	Experimental, EDO Co. freq. 80 Kc/s	Conning	Topside, forward of jackstay
High resolution	Experimental, NEL freq. 1 megacycle	Forward room	Topside, mounted above JT hydrophone
Bathythermograph	OCN	Conning	
Buoyancy control and recorders	CXJC-1 and experimental diving recorders	Forward room	Bow, near forward hatch
3 surface-ship BT's, Nansen bottles, reversing thermometers, hydrometers, and bottom samplers	Deep, 0-450 ft.; shallow, 0-180 ft.; very shallow, 0-70 ft.		Portable deck boom
Recording bathythermograph	Experimental, NEL	Mounted in watertight chamber and hung in thermal layer from bu.	

A discussion of sonar ranges is nearly meaningless in view of the small number of observations a: ie extremely variable temperature structure of the water. The thermal and salinity structure is very complex, both in horizontal and vertical directions, and is variable with the state of melting (cf bathythermograms of BOARFISH and CARP). Sonar ranges, QC QB and QLA, were strikingly poorer in the Chukchi Sea than in the Ross Sea. Of course, the differences in ocean structure (temperature and depth) are just as striking.

Some qualitative information on sonar ranges is given in Table VI. The USS CHUBB acted as target for both surface and periscope runs. An order of magnitude of sonar ranges can be appraised if one scans the observations in the table. No attempt has been made to compute the sound field for the Chukchi Sea because of the extreme complexity and lack of observations [illegible] nd transmission in the presence of positive gradients.

The dive [illegible] BOARF[illegible] on 5 August 1947 was made at a keel depth of 120 feet, about 25 feet above the bottom. The topside QLA transducer was used. Average contact ranges were 400 yards, with occasional echoes from large pieces of ice at 800 yards. The normal ice thickness was observed on the NK upward fathometer to be about 15 feet. Pieces 20 to 35 feet thick were interspersed with the thinner ice and brash. The maximum observed thickness [illegible] 40 feet. The quality of the echoes was strikingly similar to the character and [illegible] definition of shoal echoes.

The extent of the ice target, the layered thermal structure and the sound scattering character of ice contribute to non-discrete echoes.

It is noted that the vessel was cruising in uniform temperature and density layer. The topside soundhead was about 50 feet above the flat silted bottom.

TABLE VI. SONAR OBSERVATIONS, CHUKCHI SEA, USS BOARFISH

6 August 1947

Waves: height, 4 feet; period, 3 seconds; no white caps (BT shown below).

CONDITIONS

BOARFISH periscope depth, 58 feet; speed, 3 knots; course, 180° true.
Target: CHUBB on surface, speed 10 knots (two engines), circling BOARFISH, closing and opening range. Later CHUBB lay to for approach by BOARFISH. CHUBB pinging. (JT readings were taken continuously, but only readings of interest in comparison with other sonars are entered.)

QB Pinging and Listening		JT Listening		Periscope Ranges			QLA Scanning
Pinging heard	150°	Contact	150°	1800 yds.			Bottomside head — observed bottom echo ring all bearings at about 350 yds.
Screws heard	148°	held	146°	1250 yds.			
	143°	throughout	144°				
	139°	run	140°	750 yds.			
			137°				
			127°	580 yds., beam aspect			No target
							Changed to topside transducer
			086°	380 yds.			
			079°		060°	425 yds.	
	056°				058°		
	061°				053°	575 yds.	
			057°				
			054°		045°	600 yds.	No bottom echo ring showing
Screws and pinging audible			344°	560 yds.	343°	600 yds.	
			337°		333°		Target strong to 700 yds.
	327°		320°				
			288°	350 yds.	290°	400 yds.	
			267°		250°	350 yds.	
			220°		218°	425 yds.	
			211°		204°	500 yds.	Lost in shadow of conning tower. Wake on starboard very strong, crossing bow at 200 yds.
Screws heard	158°		158°	850 yds.	160°	800 yds.	Weak, behind wake from previous circle
	147°		147°		138°	900 yds.	
	142°		141°				
	131°		127°	800 yds.	120°	800 yds.	See target through wake
Ping contact 775 yds.						750 yds.	Sound head entering wake of previous run
	103°		104°	680 yds.	103°	700 yds.	
Ping contact 900 yds.	076°		077°		065°	700 yds.	
	044°		045°	620 yds.	030°	625 yds.	
Ping contact 718 yds.			023°		014°	700 yds.	
			356°		353°	650 yds.	
	334°		333°		325°	630 yds.	
	280°				280°	700 yds.	
	253°				250°	700 yds.	
	203°		203°	750 yds.	200°	775 yds.	
	159°		159°		150°	800 yds.	
	143°		145°	890 yds.	140°	800 yds.	
	128°		128°	950 yds.	128°	800 yds.	
	115°		115°		100°	850-900 yds.	
Ping contact 1000 yds.			105°		100°	850-900 yds.	
					083°	1050 yds.	Old wake distinct
	075°		075°	1300 yds. 078°	075°	1150 yds.	Old wake around head — lost contact
				1500 yds.			
Ping contact 1475 yds.	053°		053°	1560 yds.			Wake crossing bow at 900 yds., trailing across to 1100 yds.
Screws still heard	182°		175°	1740 yds.			Old wake 75 yds. ahead

TABLE VI. SONAR OBSERVATIONS, CHUKCHI SEA, USS BOARFISH

QB Pinging and Listening	JT Listening	Periscope Ranges			QLA Scanning
151-148°					
Screws spotty	110°	2000 yds.			
Screws audible 079°	079°	2150 yds.			
	Message sent via QB requesting CHUBB to lie to for BOARFISH approach				
One ping contact 2350 yds.	293°	2350 yds.			
	Lost 308° contact, target stopped				
Ping contact 2100 yds.		2050 yds. 337°			
	On approach				
No contact Reverberations intense to 1200 yds., then faint burst again at 2000 yds.		1375 yds.			Surface reverberation at 800 yds. intense
One ping contact 1160 yds.		1110 yds.			One contact
1050 yds.		1075 yds.			One contact, 1050 yds.
40% recognition 1000 yds.		1000 yds.	021°	1000 yds.	33% recognition
100% recognition 950 yds.			020°	900 yds.	100% recognition
		850 yds.			
QB required coaching from QLA to interpret multiplicity of echoes and reverberation bursts.		760 yds.		750 yds.	100% recognition Contact held into closest approach of 275 yds., 130°
Occasional contact out to 1400 yds. Reverberations noticeably decrease at 1500 yds. Four single contacts between 2100 and 2300 yds.					Contact held on opening range to 1075 yds. Intense surface reverberation at 800 yds.

7 August 1947 — Chukchi Sea

Waves: height, 4 to 6 feet; period, 3 to 4 seconds. (BT shown below)

CONDITIONS

BOARFISH on surface, circling target at speed of 10 knots; ship roll about 20° (total angle).
Target: CHUBB at periscope depth, speed 3 knots, course 190° true. Contacts very spotty, both QLA and QB; high reverberation level and much air carried under hull by sea.

QB Echo Ranging	Periscope Bearings			QLA Scanning
				Intense reverberation out to 1000 yds.
Contact 1175 yds. 038°	040°	038°	1100 yds.	
1000 yds. 038°		043°	1100 yds.	
950 yds. 050°		050°	825 yds.	
750 yds. 070°	069°	067°	700 yds.	Sector 100° to stern intense turbulence
		077°	610 yds.	noise direction opposite to running of sea
		090°	500 yds	
Sector from 70° to stern intense	100°			Contact lost — target aspect about 15°
turbulence noise	120°			on target's bow
	125°			
	Aspect zero angle			
	Aspect — 10° on target's starboard bow	130°	650 yds.	Contact regained
QB in shadow of QLA head	095° beam aspect about 1000 yds.			Reverberation too intense
No contacts	025°	025°	600 yds.	Doubtful contact
	054° beam aspect	039°	550 yds.	One contact only
No contacts	075°			
	090°			
	Estimated 600 yds.			No contacts

The bottom echo was persistent and quite strong at 400 yards range. Data of the entire dive are given in figure 43 and the geometry of the operation is illustrated in figure 44 (horizontal and vertical distances plotted to same scale). Beyond a range of 300 yards, the normally effective sound cone of the QLA intercepts both the ice overhead and the bottom below. Contact on a deep target would be held on approach to zero range, in comparison with shallow targets which pass into the "cone of silence" above the sound beam. Contact was lost on ice 30 feet thick at 100 yards range, and on ice 10 feet thick at 200 yards range. Obviously, discrimination of target depth by observation of

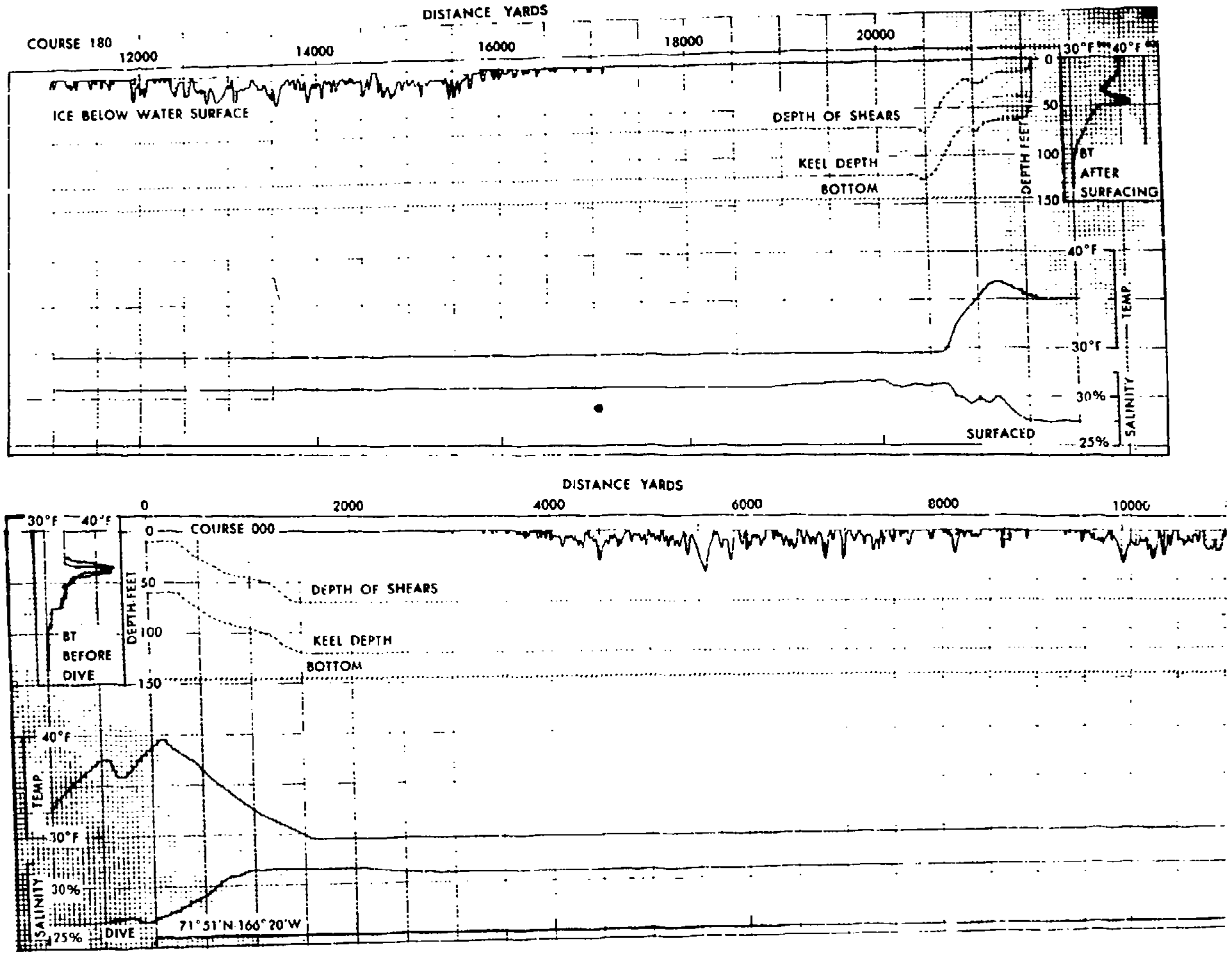


Figure 43. Data for BOARFISH under-ice dive, 5 August 1947.

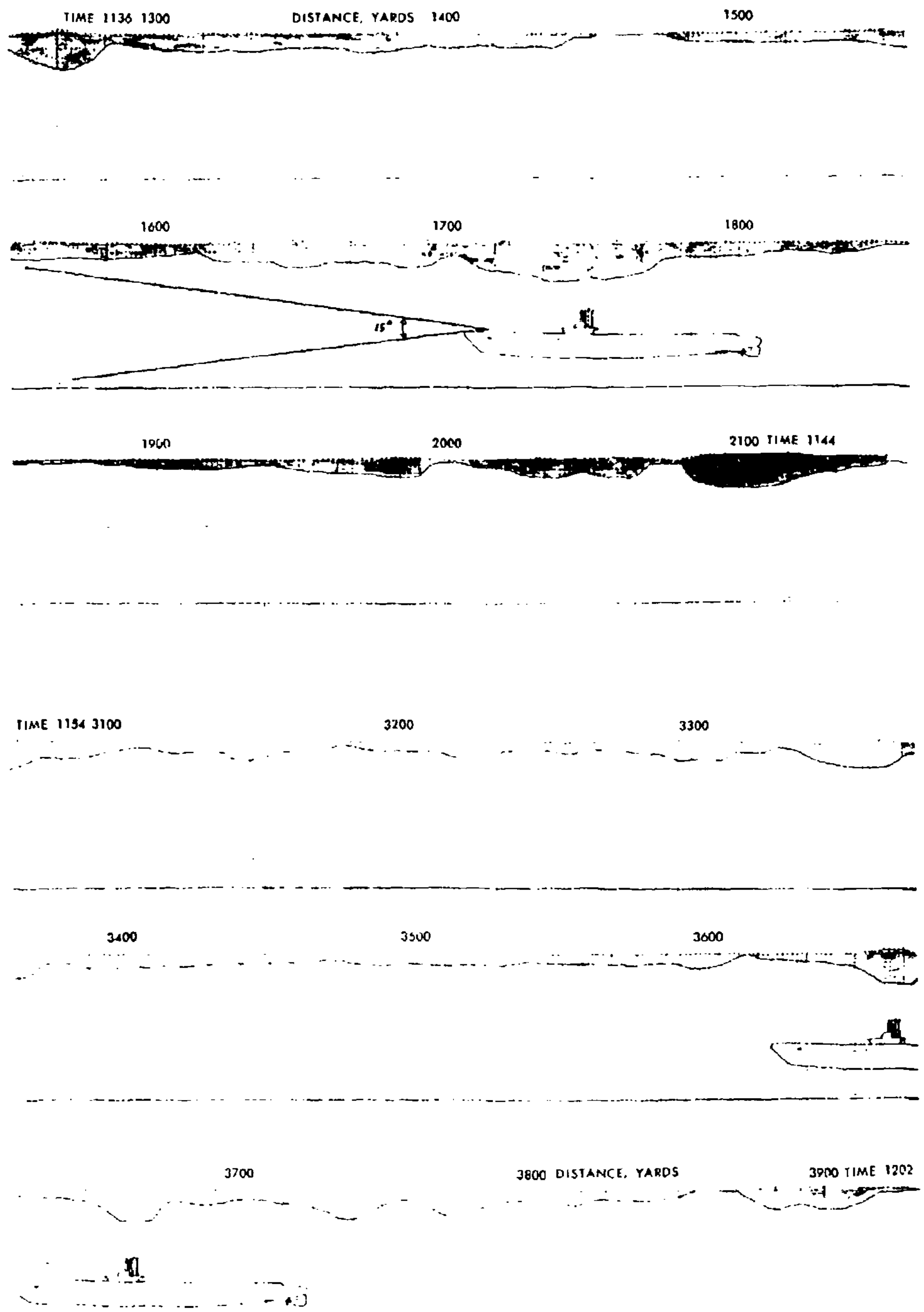


Figure 44. Under-ice dive, USS BOARFISH, 5 August 1947.

lost-contact range acts in an opposite direction to the safety of the vessel. It is a gross misconception if one visualizes the normal duty of the QLA, and other sonars, to be the guidance of the submarine past and between submerged ice stalactites that extend to its depth. The choice of safe cruising depth is determined from oceanographic data of the area (bottom contour, density gradients, expected ice thickness for particular season), observed physical properties of ice surface, and experience. The QLA provides a continual check, or index, on the bottom contour and the character of the ice canopy (open patches of water, flat floes, conglomerates of brash ice, rafting, and so forth). Knowledge of unexpected changes in these characteristics is essential to the under-ice navigator. The problem is not that of threading one's way along a complex obstacle course, though, of course, much later some particular *strategical* situation may require an arctic submarine to thread its way between ice obstacles. A detailed report and evaluation of the operation of the QLA equipment is given in Appendix A.

The QLA scanning sonar was used to evaluate lakes and the amount of brash which usually clutters each lake. The lake was plotted in; course and speed were then chosen to reach a clear position; and a vertical ascent was made. The type NK upward fathometer detected any ice that lay overhead during the ascent. During one ascent by the CARP, a piece of ice was brought up on the afterdeck (fig. 45 and 46). This accident would not have occurred if type NK fathometers had been mounted aft of the conning tower. It should have been obvious prior to the CARP's cruise that the most simple, yet effective, scheme for providing sonar coverage directly above the vessel is the installation of NK upward fathometers fore and aft; at least, it now is obvious. Prior to the CARP's cruise it had been assumed that the angle of ascents would be shallow, requiring zenith scanning for wide area of coverage. However, the success of the CARP in executing controlled vertical ascents showed that only immediate vertical coverage was needed. The installed zenith scanners did permit the accident shown in figures 45 and 46, an aft deck fathometer would preclude this type of accident.

An example of a dive by the CARP (5 Sept. 1948) from one lake to the adjoining lake separated by a floe about 400 yards across is shown in figures 47 and 48. It was observed on QLA that the lake contained considerable glacons and that there was a clear area of about 350 yards between the edge of the floe and the glacons. The surfacing order was given one and one-fourth minutes (125 yards) after the 808J topside fathometer indicated the conning tower had passed from under the floe. The ascent is shown at the extreme right of the 808J record (fig. 47). The floe lay about 100 yards astern (fig. 48), and a glacon about 200 yards forward of the bow.

Under-Ice Echo Sounder (NK) Records

The type NK (808B-808J) fathometer is a portable unit manufactured by the Submarine Signal Company, Boston, Mass.* The magnetostrictive sound head consists of two nickel stacks mounted in a wooden case and is shock excited (nominal frequency 22 kc.). The recorder has four scales at two different speeds, that is, A scale, 0 to 55 feet/fathoms, B scale, 35 to 90 feet, fathoms, C scale, 70 to 125 feet/fathoms, and D scale, 100 to 160 feet fathoms.

Sample records are shown in figures 49, 50 and 51. The denser, narrow trace is due to reflections from the open water surface. The vertical scale is the distance above the deck. Two scales, B and C, were used, depending upon the ice thickness. The apparent

* Some reports have incorrectly stated the BOARFISH and CARP carried type NK-7 fathometers. Commercial types 808B and 808J (similar to Navy 1940 type NK) were installed. There is an essential difference; the sectored scale is furnished on the 808B-J types.

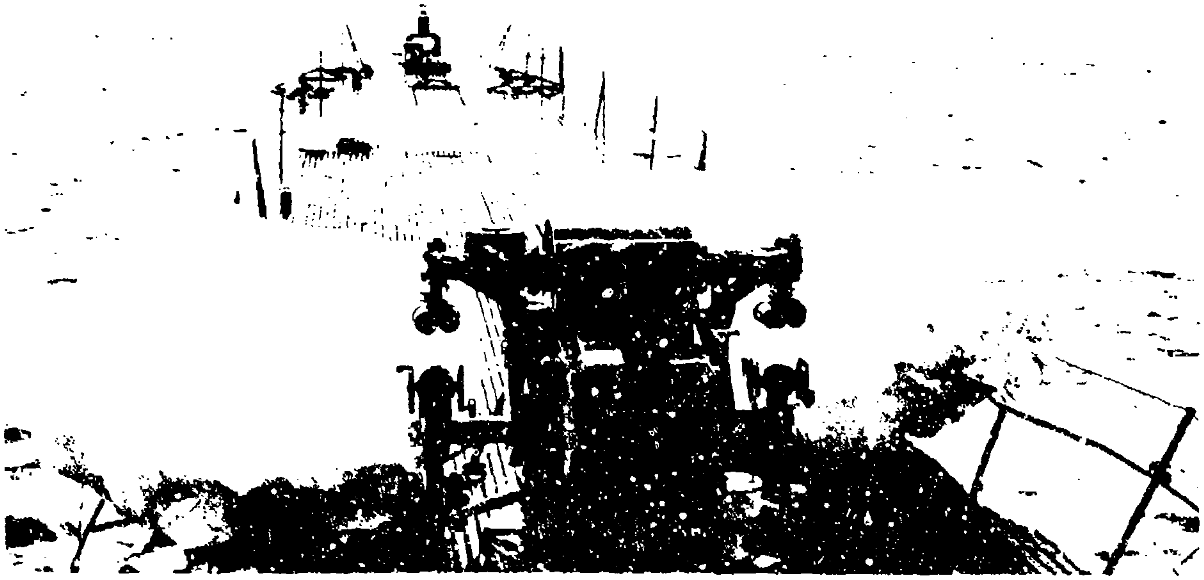


Figure 45. Ice caught on deck during vertical ascent of USS CARP, 5 September 1948

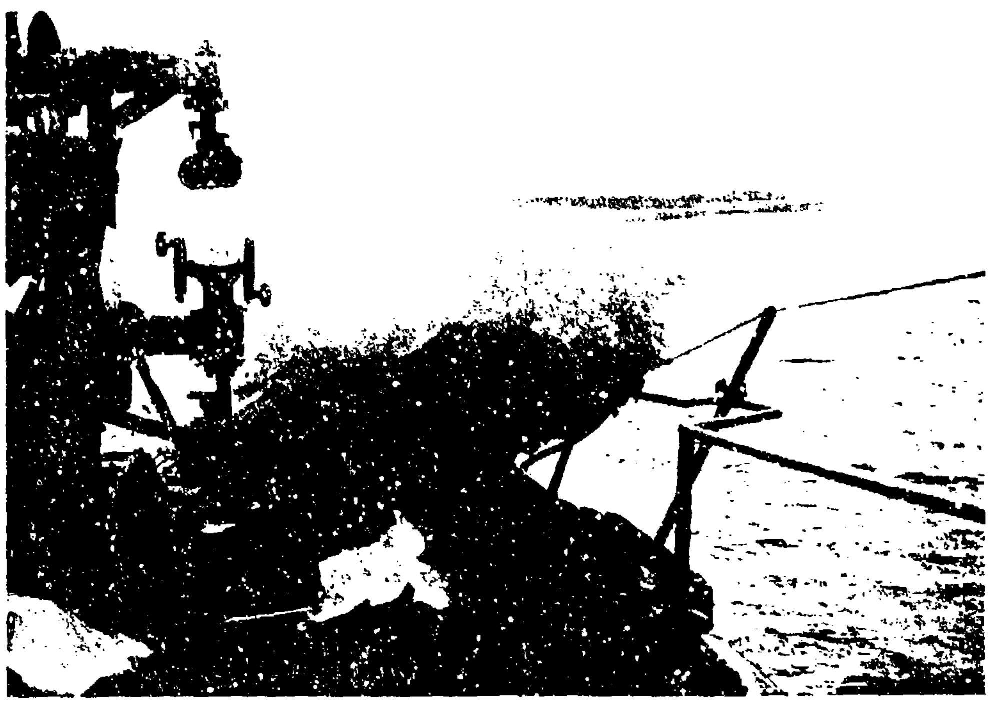


Figure 46. Ice caught on deck during vertical ascent of USS CARP.

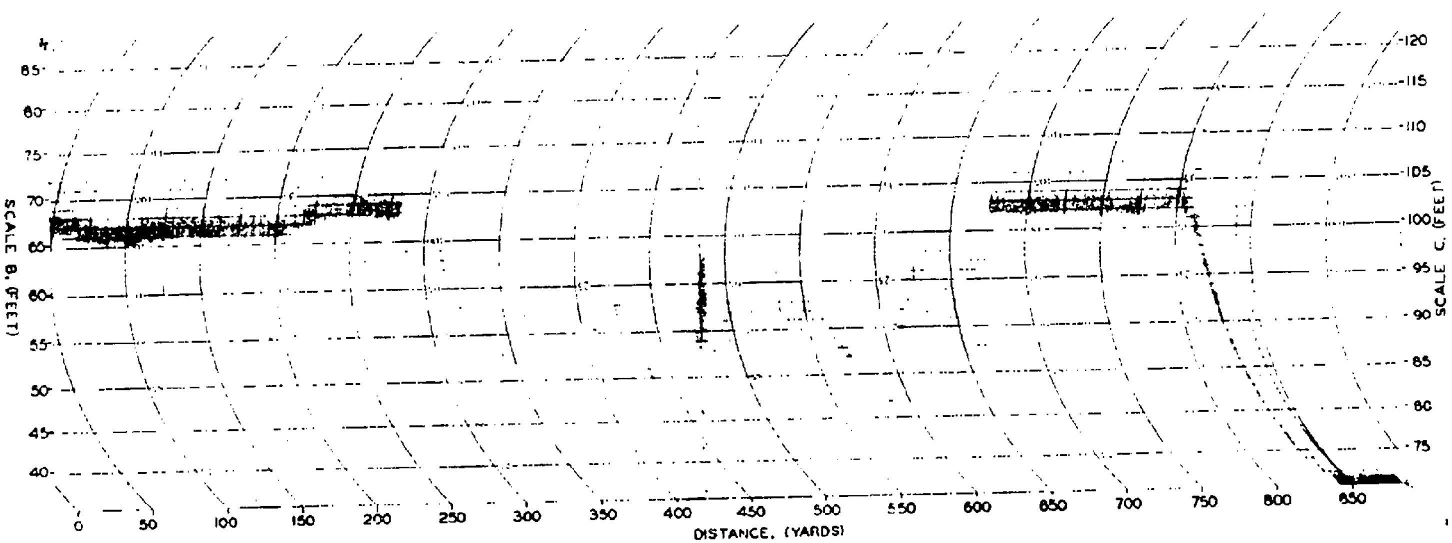


Figure 47. Topside fathometer (808J) record of dive under floe by USS CARP, 5 September 1948.

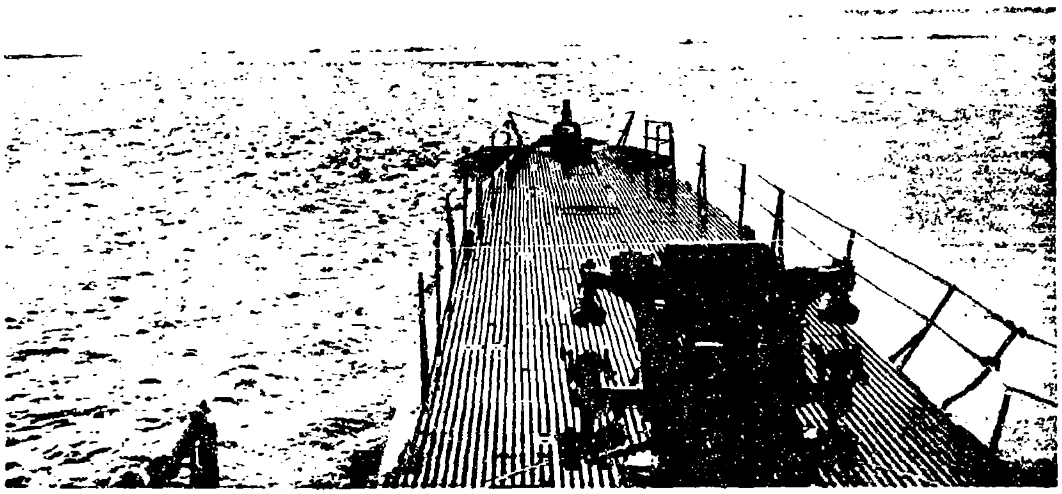


Figure 48. Floe under which CARP dived, 5 September 1948.

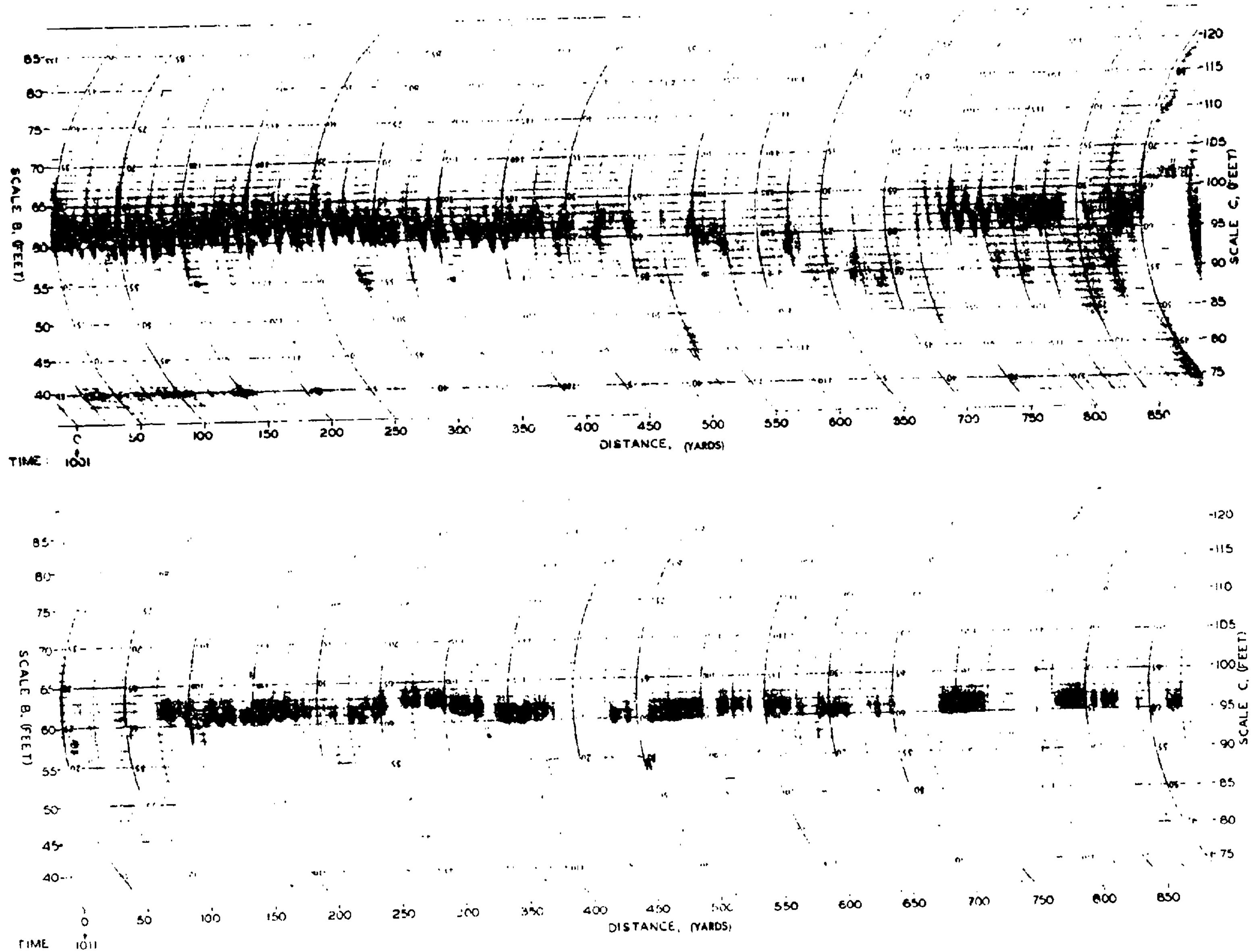


Figure 49. NK fathometer record, USS SCARFISH under-ice dive.

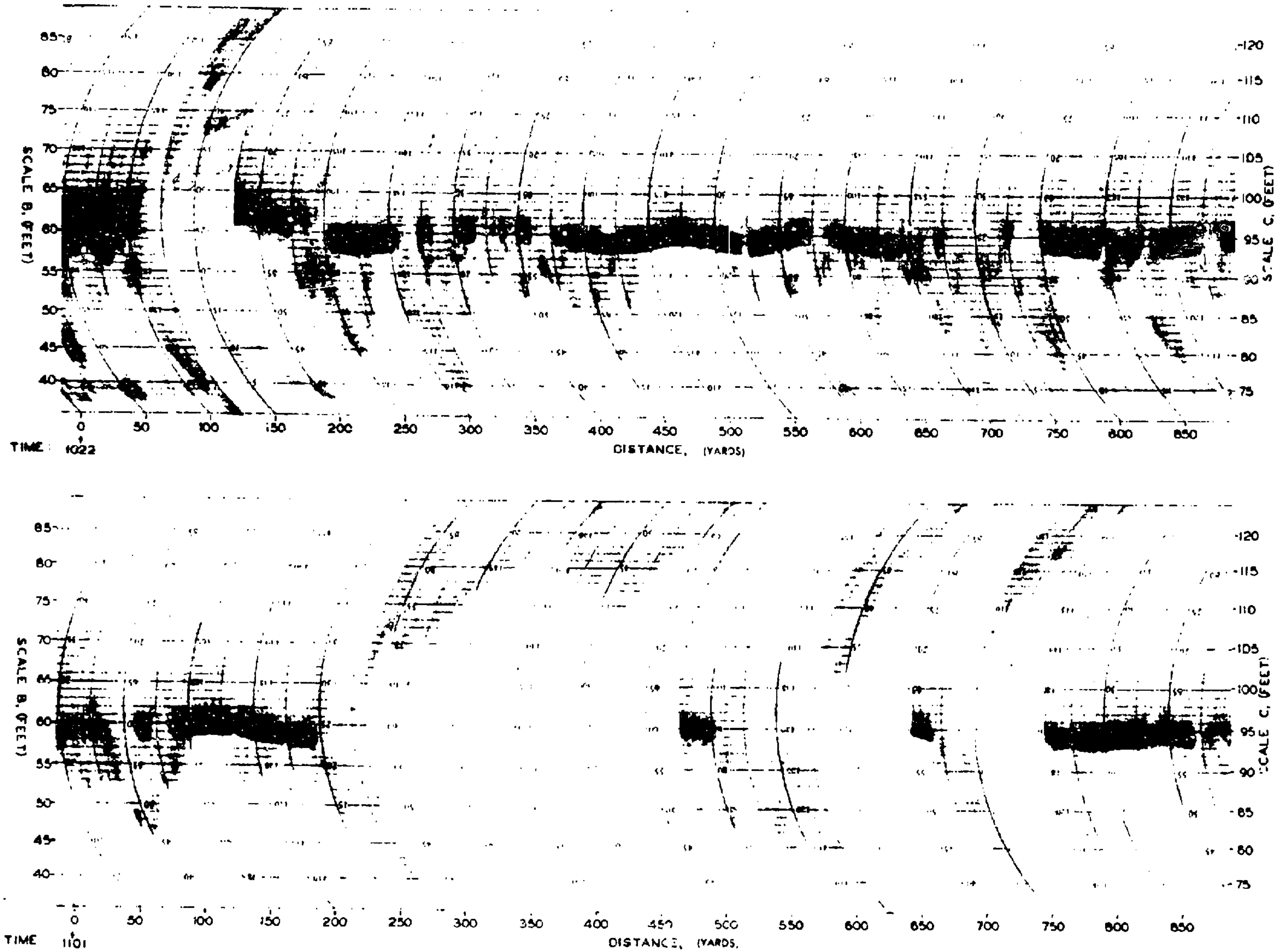


Figure 50. NK fathometer record, USS BOARFISH under-ice dive.

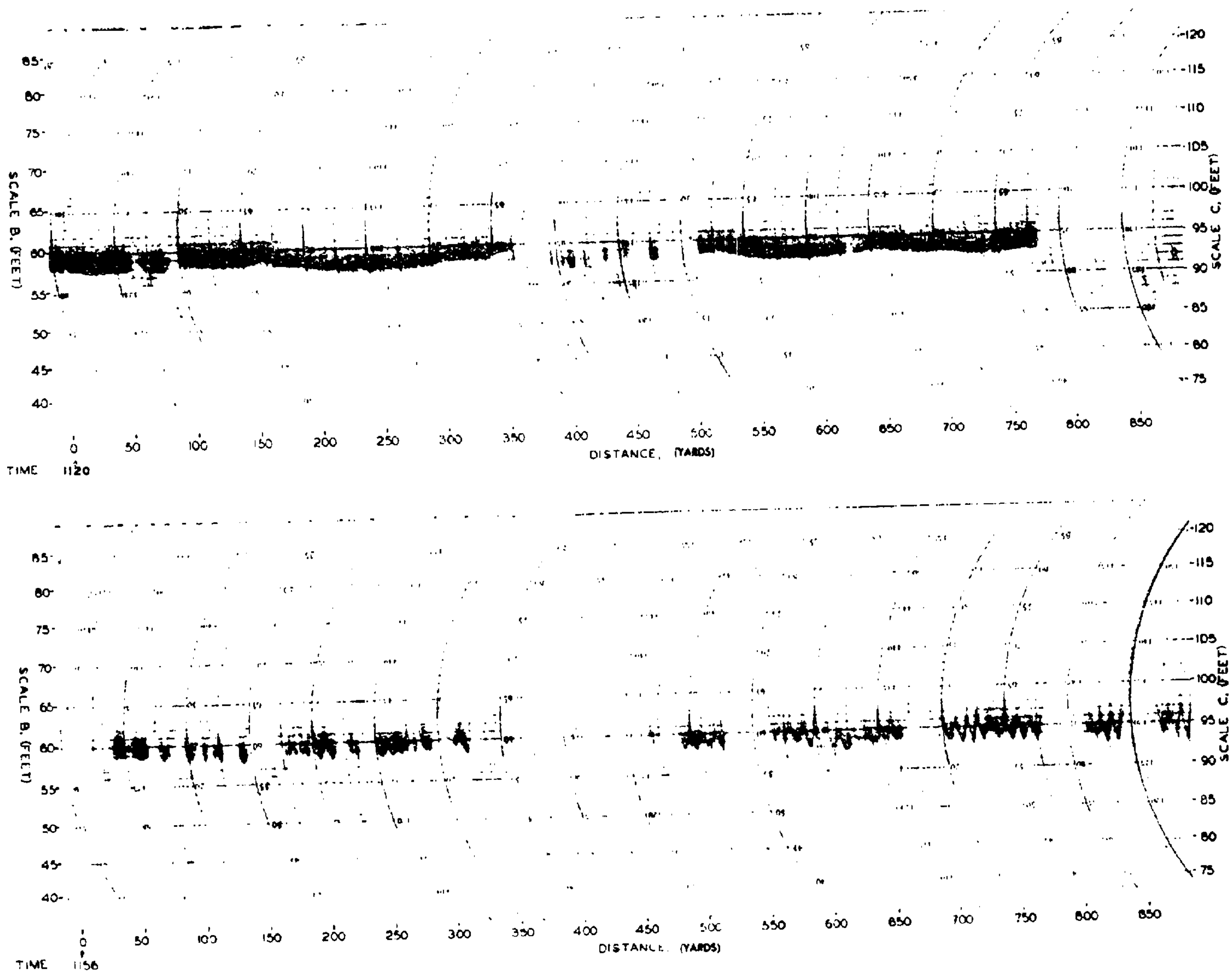


Figure 51. NK fathometer record, USS BOARFISH under-ice dive.

upward displacement of the trace indicates B-scale recording. Waves 3 to 4 feet in height are shown on the record of figure 49. They were observed near the edge of the ice. The waves were selectively damped a few hundred yards inside the edge of the scattered ice.

The NK records have considerable distortion since the vertical scale is greatly expanded over the horizontal scale. Sample records were replotted to uniform scale in order to present the dive in proper relation (see fig. 44).

In comparison to the water surface trace, the ice echoes appeared as broad traces of lighter but uniform density and variable width, depending upon the ice thickness. Distinct, separate floes are shown, as well as nearly contiguous floes dispersed with occasional small pools. The uniform density of the trace over the entire depth of the ice is most interesting and suggests that the impinging sound is scattered back from throughout the body of the ice rather than spectrally reflected by the water-ice interface. The general appearance of the ice trace is very similar to that of a surface ship's wake observed from beneath by the same fathometer mounted on the deck of a submarine (USS S-18, October 1943). A sample wake record (fig. 52) taken from reference 7 is reprinted for comparison.

The diffuse appearance of the ice echo is probably caused by internal scattering of sound; the ice is not a spectral reflector in the 20-kc. frequency region.

The variation of the recorded echo trace with ice depth has been computed for two cases: (1) volume scattering; i. e., sound appreciably penetrates and is scattered back from throughout the body of ice, and (2) diffuse reflection; i. e., sound is scattered back from a very thin layer of the lower surface. For case (1), volume scattering, it is assumed that the ice is fairly transparent and that a constant amount of sound energy is scattered back per unit volume of ice. For case (2), it is assumed that the energy scattered back per unit isonified area of the water-ice interface is constant and independent of the angle of incidence.

The effective "ping" length for the NK equipment was chosen to be 2 feet (0.4 millisecond) (fig. 53). The directivity pattern for the transducer is shown in figure 54. The curve marked "Narrow plane" refers to the short dimension of the transducer face, and "Wide plane" refers to the long dimension (transducer is rectangular, nickel stack, 6⅝ x 3⅜ x 4 inches).

The step-curves were used in the "summation" of energy scattered back to the transducer. The computed curves for three different thicknesses of ice are shown in figure 55 for each case — volume scattering, and diffuse reflection. The relative sound pressure (db) is plotted against the distance above the transducer (depth in feet) analogous to the experimental conditions. The depth of the transducer is taken to be 100 feet. Two "tails" are shown at the upper end of the curves in figure 55 which correspond to two choices of the contribution from the ice above the sea surface. The right-hand "tail" appears if it is assumed that the ice continues for some distance above the water and the scattering remains constant per unit volume The left-hand "tail" corresponds to the assumption that the ice stops abruptly at the sea surface. The true representation likely lies between these two extremes.

It is noted that the curves for volume scattering rise fairly steeply, but fall rather slowly while the "ping" travels through the ice. The curves for the diffuse reflector rise abruptly and fall much more rapidly than those for volume scattering. The fall would be very rapid if the transducer lobe pattern were narrow.

The dynamic range of the NK recorder is limited because of the response characteristics of the recording paper. The dynamic range curve, figure 54, was obtained by measurement of the optical density of the recording paper with a reflection densitometer

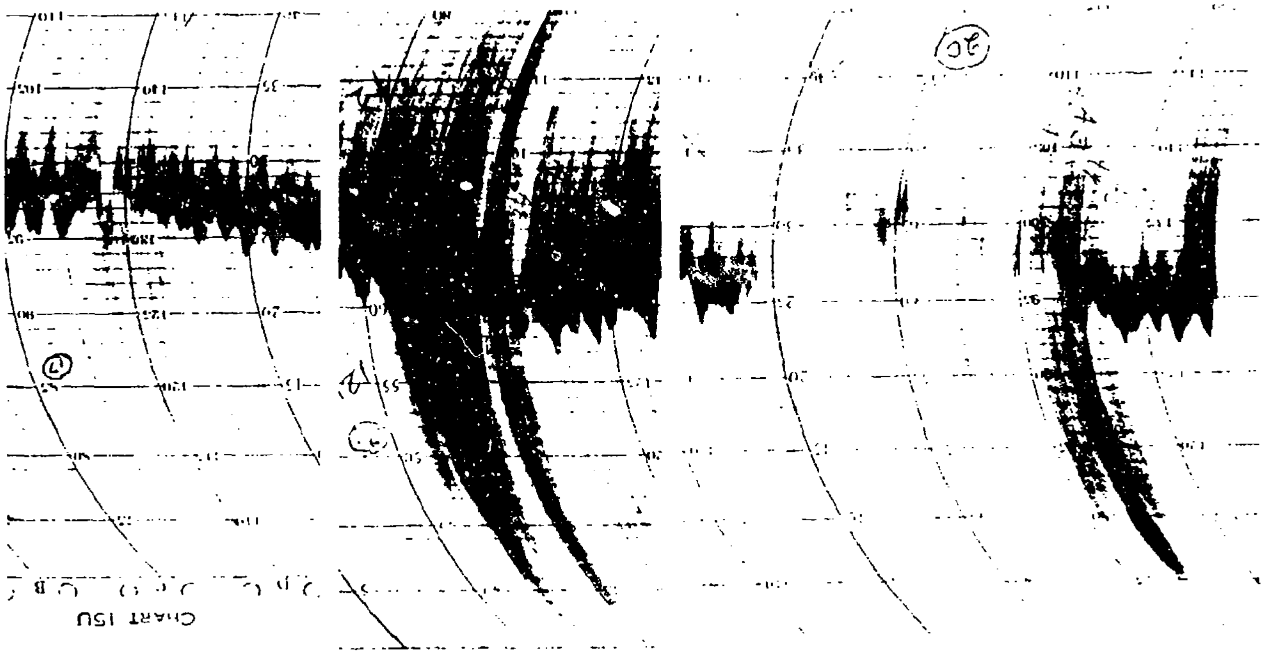


Figure 52. NK record of surface-ship wake observed on USS S-18, October 1943.

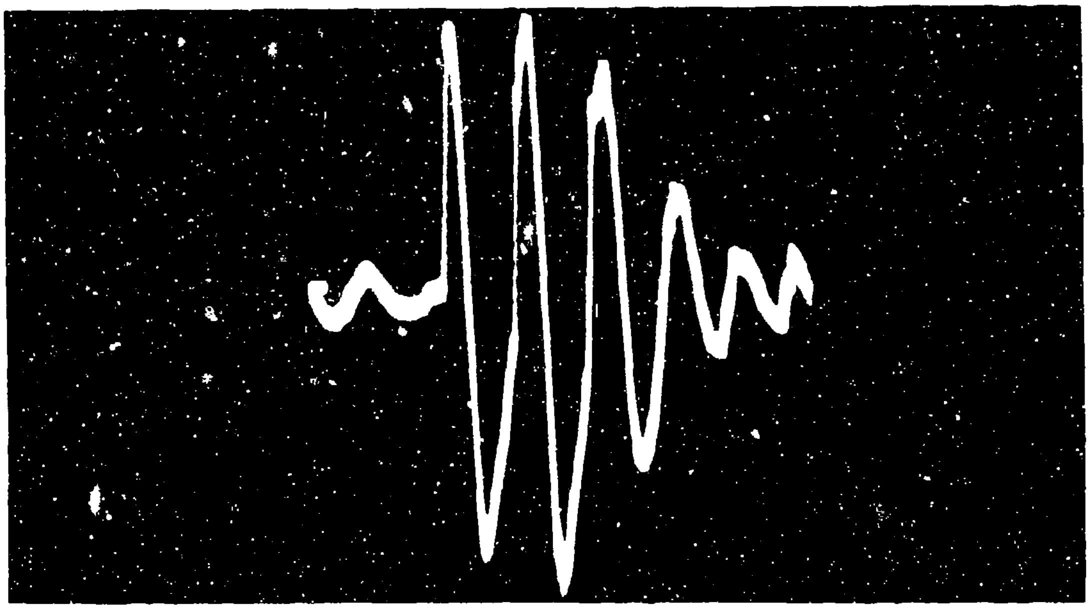


Figure 53. Oscillogram of outgoing ping, NK fathometer.

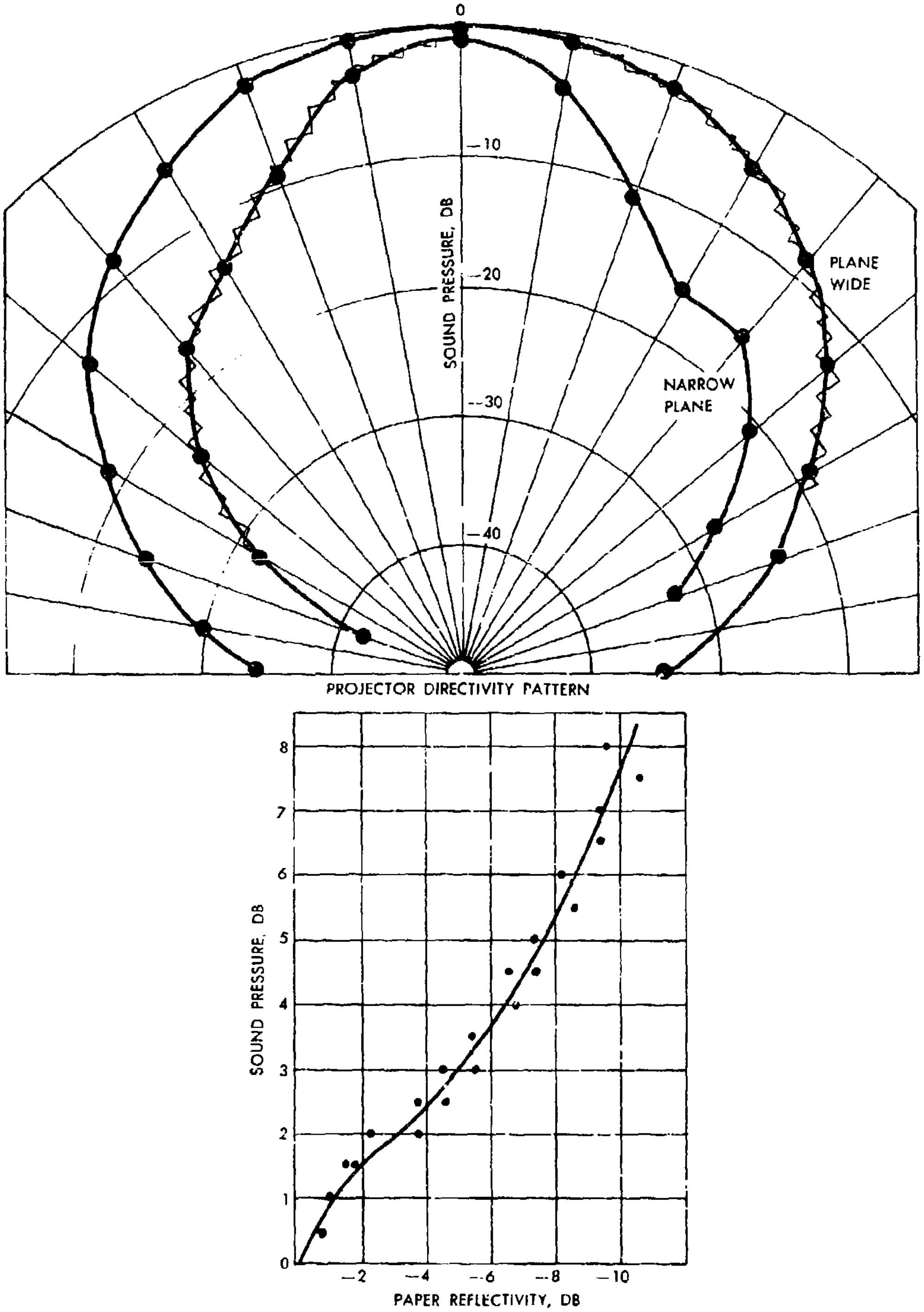


Figure 54. NK projector pattern and response characteristics of recorder paper.

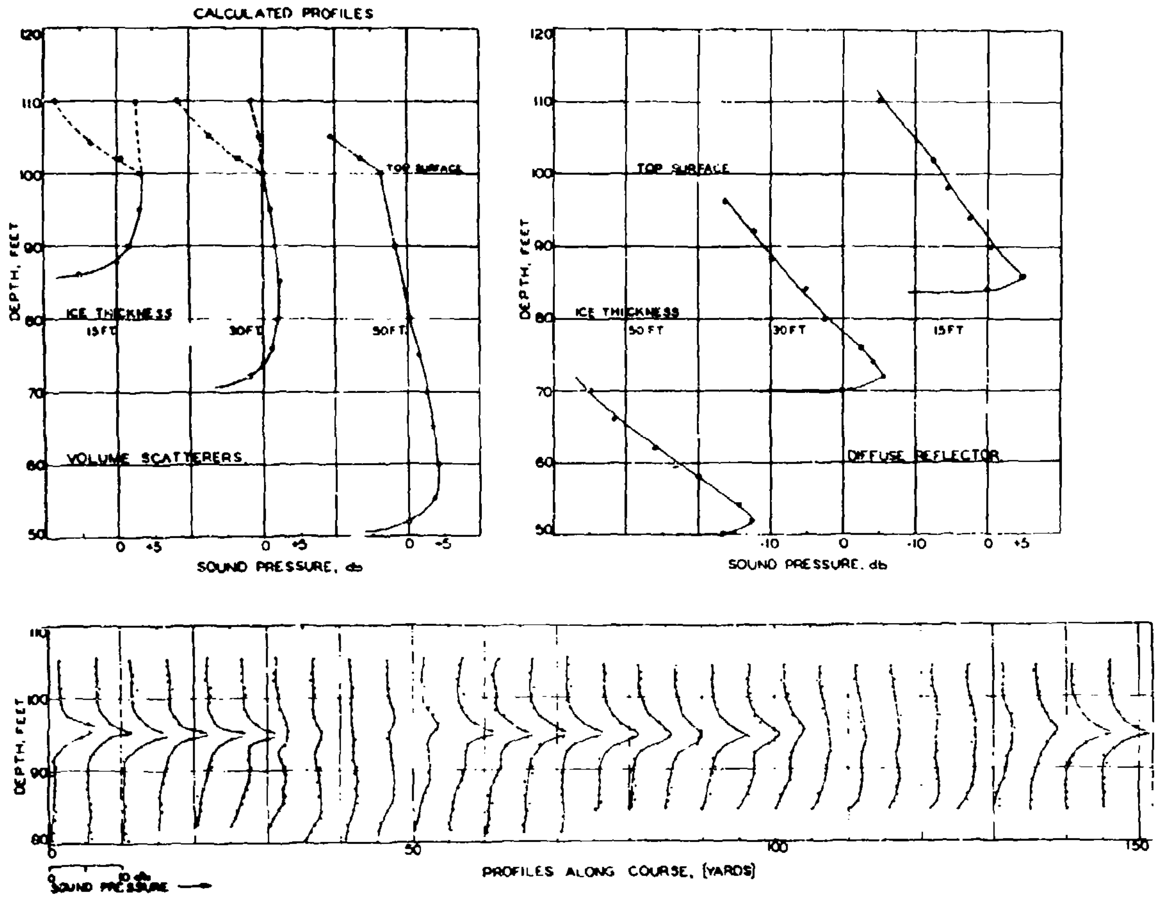


Figure 55. Observed echo profiles and calculated profiles for volume scattering and diffuse reflection.

for various acoustic pressures (constant receiver gain). In the field, the operator normally sets the receiver gain sufficiently high to just record a distinct trace of medium density, which is a dynamic range of about 5 db above no visual trace. The profile curves of figure 55 would therefore, be clipped by the recorder about 5 db below their peak values. If this clipping is kept in mind, it is seen that the observed profiles, figure 55, are similar to those for volume scattering. The observed profiles were obtained by measuring the density of the NK records with the reflection densitometer and the given dynamic range curve. A profile was taken each strip of record, corresponding to a 5-yard distance along the submarine course. Thirty profiles for a distance of 150 yards are shown. Each profile is plotted in relative sound pressure (db) above its own base line corresponding to no visual trace. The water surface appears very distinct as a sharply rising curve which reaches saturation density of the recording paper. The ice profiles rise less abruptly and then remain constant to the range of the upper surface. The saturation of the trace for the water surface reflection precludes any comparison of the target strength of the ice with that of the water-air interface. This information is needed and should be measured in subsequent arctic experiments.

The volume scattering by sea ice is probably due to the entrapped air bubbles, analogous to the similar phenomenon in ship wakes. It has been shown that for wakes, which may contain bubbles of widely varying size, the large contribution of scattered sound energy results from bubbles resonant to the frequency of the impinging sound wave.[8]

The diameter for resonant bubbles in wakes near the surface for 20-kc. sound is about 0.3 mm. A number of ice chunks were inspected and it was noted that many bubbles were entrapped in the ice. The bubble diameter was estimated to be 0.1 mm. Other ice samples were masses of packed, uniform crystalline spheres about 0.5 mm. in diameter. Air bubbles were not observed within the crystalline spheres, and it was not clearly ascertained whether or not minute bubbles might exist in the solution filling the interstices between the spheres. It has been pointed out in numerous discussions[9] of the properties of sea ice that air bubbles form within the ice during the freezing process. If the temperature of sea water (35 $^0/_{00}$ salinity) is lowered, needle crystals of pure ice begin to form at about 28.5 degrees F. Between this temperature and 17.2 degrees F., a lattice of pure ice forms which entraps brine cells. At the latter temperature, sodium sulfate begins to precipitate, and finally at —9.4 degrees F. precipitation of sodium chloride begins. Dissolved air comes out of solution in the form of small bubbles during the freezing process, though sometimes the bubbles are smaller than can be detected by the unaided eye. The faster ice freezes, the larger and more numerous are the bubbles. Newly frozen ice usually contains more air in the topmost layers.

It is believed that some air penetrates into the ice from the surface during late spring and summer. Ice in the upper layers melts from within owing to the brine content. The melting begins around the brine cells. The transformation of ice particles into water in the brine cells is a diminution in volume and gives rise to the tendency for small vacua to be formed within the ice lattice. These spaces are filled with air from the atmosphere, not with water from below, since the ice on the underside is tight. Melting starts in the topmost layers inside and works down through the ice. After advanced melting, the ice is porous, and the brine trickles out leaving ice of nearly zero salinity.

The air content of sea ice with variations in temperature, age, depth, rapidity of freezing, and so forth, presents many problems for the study of the acoustical properties of sea ice. These are of primary importance if sonar is to be successfully applied to submarine operations in polar areas.

Experimental Scanners

Two experimental scanners were tested on the CARP: (1) a zenith scanner built by the Edo Corporation, College Point, N. Y., and (2) a high resolution (1-mc.) scanner built by NEL. Both scanners used a "pulse-time travel" method.

The Edo scanner uses a transducer mounted in a hemispherical plastic dome (fig. 56), which scans in the vertical plane and can be trained in azimuth. The nominal frequency is 85 kc., and presentation is by c-r tube. Two range scales are available, 100 feet and 500 feet. The unit was designed and built in a brief period. The construction is good, and the unit worked well within its capabilities (cf. ref. 6). However, the equipment was operationally ineffectual, partly because of the inherent scanning difficulties of pinging systems at short ranges with oscilloscope presentation. Aural echo information would supplement the visual target identification.

The high resolution scanner was designed and built at this Laboratory in about four months. The work was done in haste and, necessarily, pieces from various available

Figure 56. Hemispherical dome, Edo zenith scanner.

equipments, both sonar and radar, were used. Despite the hasty construction, the unit answered important questions with regard to the method of attack on the sonar problem.

The equipment is a pinging system; nominal sonar frequency is 1 mc. The projector and hydrophone are circular quartz crystals, 2 inches in diameter. They are mounted in oil-filled cylinders with stainless-steel windows, 0.001 inch thick. The ping length is between 20 and 40 microseconds, and the effective angle is probably between 1 and 2 degrees. The echo is presented on a paper recorder similar to that of the NK-1 fathometer. The projector-hydrophone assembly scans in the vertical plane and was mounted on the JT hydrophone in order to provide training in azimuth (fig. 57). The cor[illegible]ipment was installed in the forward room (fig. 58).

The maximum observed range for the free sea surface was about 100 feet. The reflection coefficient of the water-ice surface appeared to be appreciably lower. The appearance of the recorder trace suggests that at 1 mc. the ice is a diffuse reflector. The acoustic output and amplifier gain are not known, since the equipment was constructed in too much haste to provide these measurements. Details of the equipment will be given later under a separate report.

No operational need arose for a scanning device of high angular resolution. The inherent slow scanning rate reduced its effectiveness during the dives to nearly zero. This high-frequency, high-resolution method will be used later in the design of small devices to protect the periscope.

The important conclusion is that zenith scanning devices must have rapid, continual presentation, and are second order refinements in under-ice instrumentation. A zenith scanner is not a prerequisite for successful navigation of the Arctic Ocean.

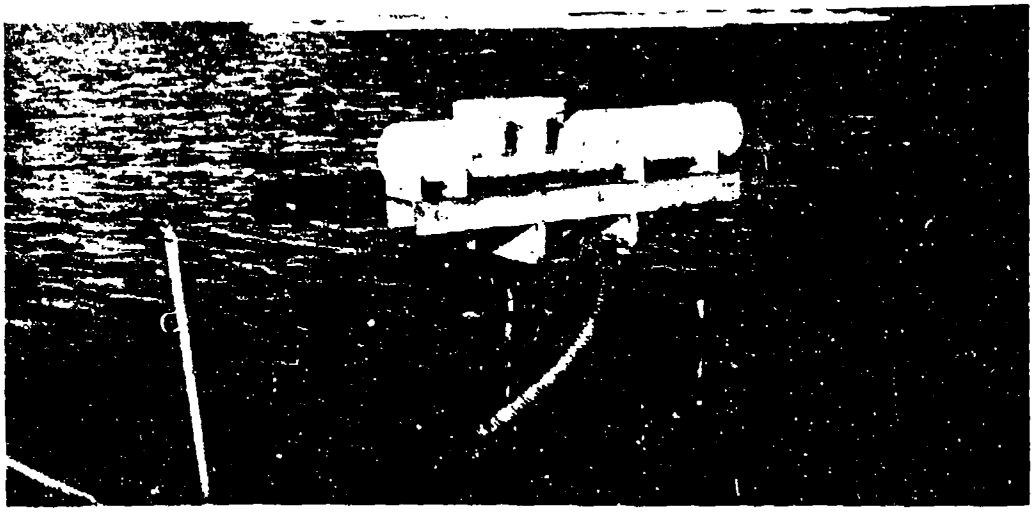


Figure 57. Projector assembly, 1-Mc pinger (guard cover in place).

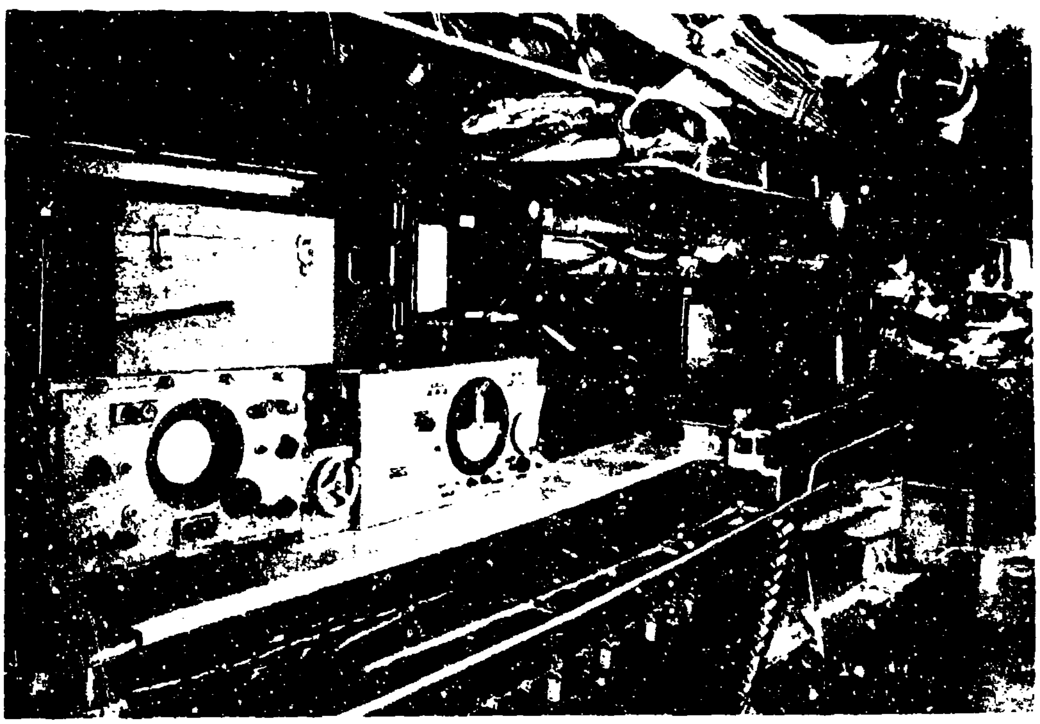


Figure 58. Control equipment, 1-Mc pinger (forward room, USS CARP).

PROGRAM FOR RESEARCH

Conclusions based on the three completed field studies are:

1. The reality of a polar submarine that can navigate the *entire* Arctic Ocean is not only admissible, but may be an immediate practicality.
2. The prerequisite equipments for under-ice navigation are standard, available equipments, though the techniques of interpretation are new. The first order problems of polar sea operations are resolved directly or by modifications of present equipment.

It is neither the purpose of this report nor the prerogative of an undersea physicist to discuss the tactical situations or strategical and political implications imposed by the conclusions. It is his responsibility to provide the maximum information and tools for any ocean operation, in particular, for a new operational area. The tactical applications and feasibility of an arctic submarine have been discussed by Lt. Comdr. Charles Hendrix, USN, while attached to the Office of Naval Research,[10] and by the Naval Examining Board of the NAUTILUS Expedition.[1] Also, a great deal of valuable information has been given by Sir Hubert Wilkins on the expedition in which the first submarine penetration of the Arctic Ocean was made in 1931. The political implications are discussed by Dr. Shelesnyak and many others,[11] and the activities of the Administration of the Northern Sea Route, U.S.S.R., are well recognized.[12]

The specific major conclusions of the three completed operations are:

1. SENNET: The maneuverability of a submarine in ice and the amount of punishment by ice that can be withstood was demonstrated. Navigation by sonar in the vicinity of icebergs was found successful. Scanning sonar is a prerequisite.
2. BOARFISH: Extended under-ice navigation was demonstrated and is practical. Scanning sonar furnished a major part of the solution.
3. CARP: Vertical dives and ascents were made in ice lakes and leads and unquestionably demonstrated that diving control is practical in ice areas. Sonar needs are simple.

The purpose of the laboratory program prior to the BOARFISH cruise was the adaptation of submarines to operations along the fringe of ice areas. The ice was anticipated to afford unequalled protective cover for submarine operations. The objective later expanded to the study of a submarine which is to penetrate to any part and cross the Arctic Ocean. The problem has resolved into two avenues of attack: (1) oceanographic and sonar studies of arctic areas, and (2) the modification of a fleet-type submarine for the further study of under-ice operations. The plans for conducting this research are discussed in the remainder of the report.

Oceanographic-Sonar Studies

The oceanographic program calls for a fairly comprehensive study of the Bering and Chukchi Seas. Important items are listed.

1. Ice — seasonal extent, thickness, form, and polynyas.
2. Currents — depth, cause, season, and relation to wind and ice movements.
3. Water structure — density, temperature, salinity.
4. Bottom — sounding charts, relation to currents and ice.

Some preliminary observations were made during 1947 from the USS NEREUS (AS17) which was equipped with basic oceanographic equipment. The results will be reported under separate cover.[3] This experience provides first-hand interpretation of the results

of past expeditions — for example, the very important Maud Expedition – which furnishes basic information across the north Siberian shelf.[13]

One of the most serious needs is for data on sound propagation in high latitude areas. Positive temperature gradients prevail in these areas. No observations have been made on the sound field under these conditions; even the order of magnitude of the problem cannot be established. The temperature gradients are sharp and intense (see fig. 14). Qualitative observations from the BOARFISH suggest the essential question: Are the positive temperature gradients sufficiently intense to defeat any sonar (ranging or listening) on a surface ship attempting to detect a target below the gradient; that, is it a prerequisite that the target and detecting sonar must be on the same side of the gradient?

Positive gradients present difficulties with which we have neither experience, observed data nor theoretical calculations. The Royal Canadian Navy experienced unsolved difficulties with German U-boats in the positive water off the approaches to Halifax (cf. ref. 14).

The difficulties of sonar and the need for data on sound propagation in arctic areas are further illustrated by a few calculations of ray diagrams. The diagrams are pertinent for a submerged source which is attempting to scan the surface for small targets. Errors in the apparent location of the target because of the influence of refraction are shown. The temperature structures often change rapidly in space and time; therefore, the ray diagrams are somewhat fictional. However, at least the order of magnitude of errors in location are probably indicated.

The projector depth was chosen to be 75 feet. A surface target at 800 yards subtends an angle of 1.8 degrees with the projector. The path of the 1.8-degree ray is calculated and shown for four cases of arctic conditions (figs. 59 to 62). The last case is similar to the situation observed during dives by the CARP. Scanning results and interpretations were much better during dives of the CARP than of the BOARFISH. (Cases 1 and 2 are somewhat typical of conditions during BOARFISH dives.)

During the past seven years, a great deal of data has been gathered on sound transmission in mixed and negative-gradient water off San Diego. The results, though empirical in form, give a basis for sonar engineering. The method is costly in time, ships, and manpower. It had been planned to pursue well-defined, limited experiments which would lead to a complete theory of underwater sound. However, since the available data on sound propagation in positive-layered water are nil, we somewhat reluctantly return to the empirical method and will attempt to measure the sound field under various arctic conditions. Though the method is costly, it appears mandatory in view of the possible military urgency for sonar information in arctic areas.

An expedition is planned for the summer of 1949 to study sound propagation and oceanography of the Bering and Chukchi Seas. The laboratory vessels, USS BAYA (ESS318) and the EPCE(R)-857 will be used to conduct sound field measurements, and, in conjunction with the HMCS CEDARWOOD, will conduct oceanographic studies. The Pacific Oceanographic Group, Nanaimo, and the Pacific Naval Establishment, Esquimalt, B. C. (the Canadian oceanographic and sonar laboratories on the Pacific coast), expect to join the Navy Electronics Laboratory in these studies. It is believed that in the channels east of Vancouver Island, water conditions are nearly identical with those of the Chukchi Sea in respect to thermal-salinity layering. The similarity will be verified, and then, in these sheltered waters, a study of the physics of upward refracted sound and intense thermal layering can be made in an exacting laboratory

* Calculations prepared by M. Sheehy, Head of Analysis Section, Research Division.

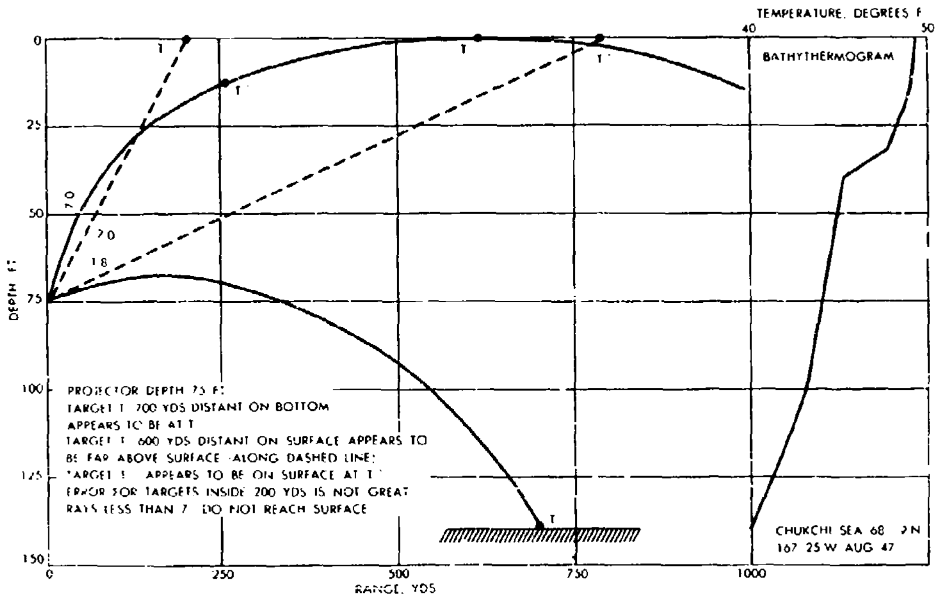


Figure 59. Ray diagram.

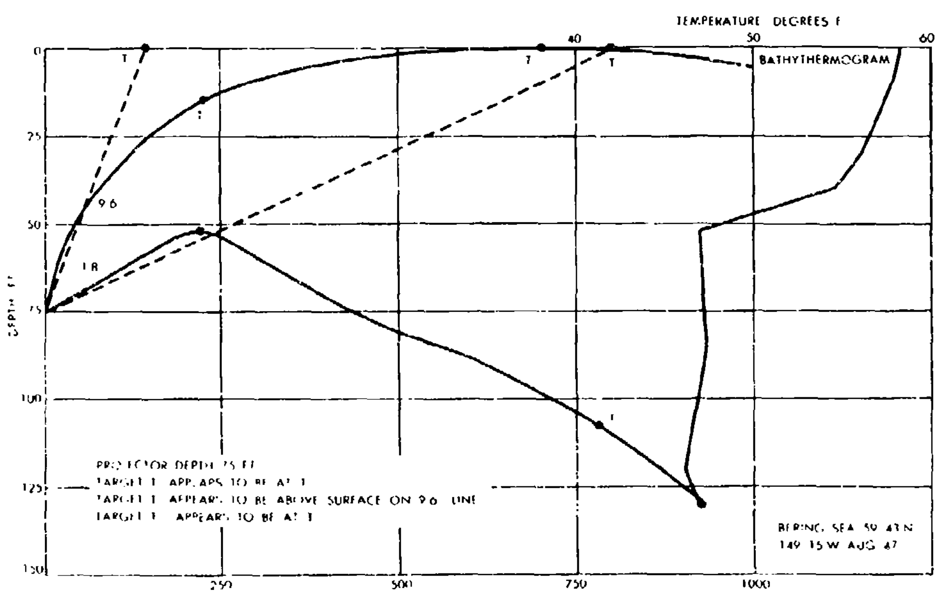


Figure 60. Ray diagram.

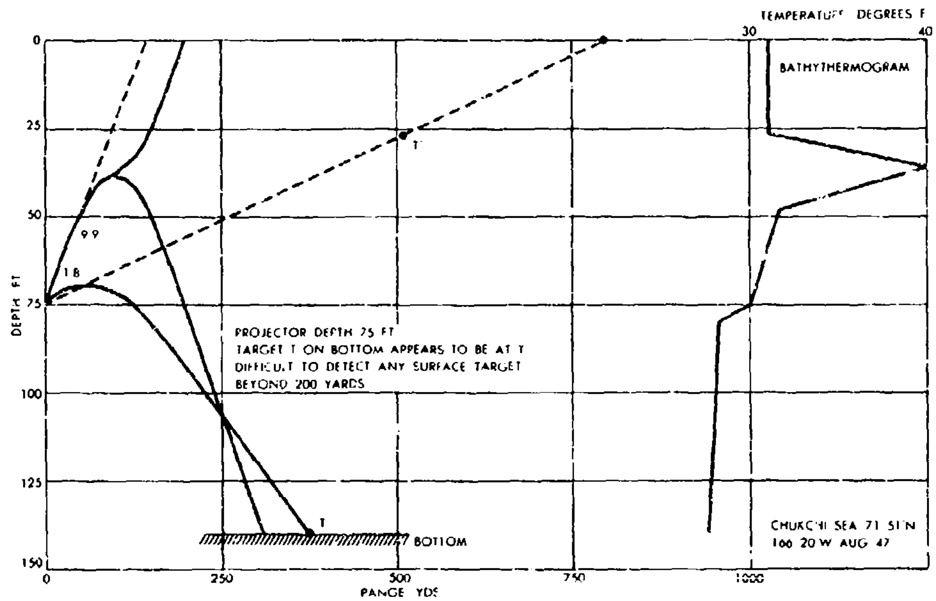


Figure 61. Ray diagram.

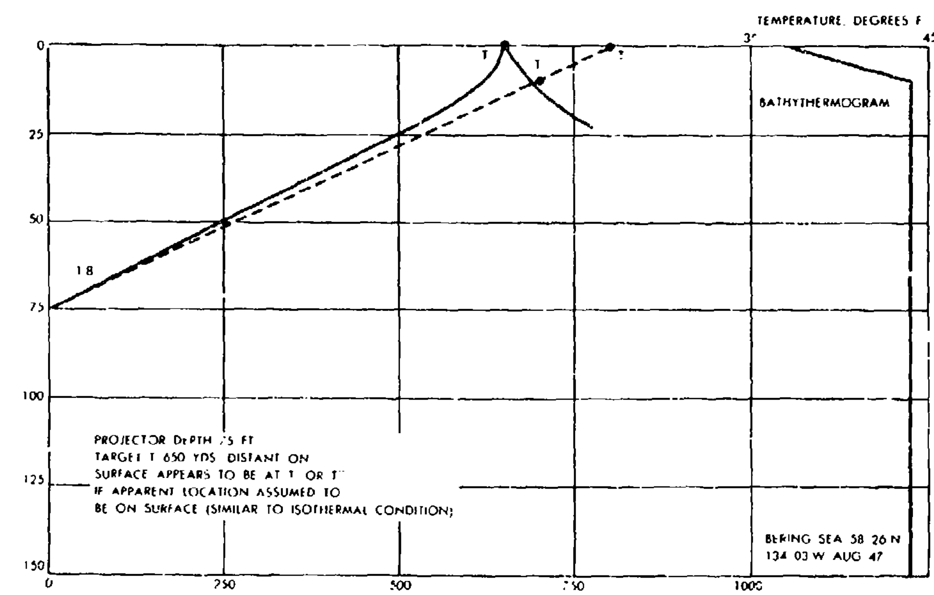


Figure 62. Ray diagram.

manner. The study is on a continuing basis in cooperation with the Canadian Naval laboratories of the British Columbia area. The oceanographic program includes:

1. Bottom topography and sediment (including geological study with respect to geographic position, size, source and transport of sediment).
2. Thermal-salinity structure (including detailed study of small areas to unravel unique dynamic stability of extreme thermal layers).
3. Horizontal currents (variation with respect to position, tide, depth, and so forth).
4. Properties of ice (structure, air content, sediment content, salinity and acoustical properties).

SUBMARINE MODIFICATION FOR CONTINUING RESEARCH

Continued familiarization cruises by the Fleet should prove valuable for introducing more personnel to arctic areas. Simple under-ice dives at the fringe of the pack, and surface maneuvering in ice provide valuable training and alleviate the fear of an unfamiliar area. However, it is most important to realize that further arctic research with the current fleet-type submarine has reached the point of diminishing returns. It is, therefore, imperative that a fleet submarine be specifically modified for arctic research. The modification is relatively simple, yet should provide, perhaps, three-fourths of the answers which will be needed to design an arctic operational vessel. Simplicity at this stage is all important.

On the basis of completed work, premises for the operation of the modified submarine can be stated.

1. Contemplated operations are for summer only at this research stage. The amount of open water throughout the arctic pack is very considerable (this point is discussed in detail in refs. 1, 10, 13, and 15).
2. Contact between hull and ice is normal and expected. The submarine is very maneuverable and can force its way through considerable ice.
3. Primary safety and choice of cruising depth is based on oceanographic data and experience. Sonar is not intended for threading a course through complexity of ice obstacles at this time. Sonar provides protection against icebergs and the major obstacles in depth. Areas of fast ice are approached with extreme caution.
4. Visual observation is to be used for all direction of maneuvering in ice when in surface condition.
5. Scanning sonar (QLA) provides required information on the ice canopy.
6. Ascents in leads and under-ice landings are practical and are guided by topside fathometers.

The modification of the fleet-type submarine will consist essentially of the following alterations:

1. The vessel should be made symmetrical by running topside keels (turtleback) to permit resting underneath ice, and by providing associated changes in topside gear (retractable sonar and radar, 32-foot periscope in control, and so on).
2. Thermal ice drills should be installed for engine supply and exhaust.
3. Minor internal changes of equipment must be made to expedite navigation by sonar and to operate thermal drills.

A schematic proposal for the modification is given in figures 63 to 67, and the modifications are listed in Table VIII. Detailing of buoyancy changes for stability are not given; the proposal is for initial planning and discussion. Presentation of a diagram

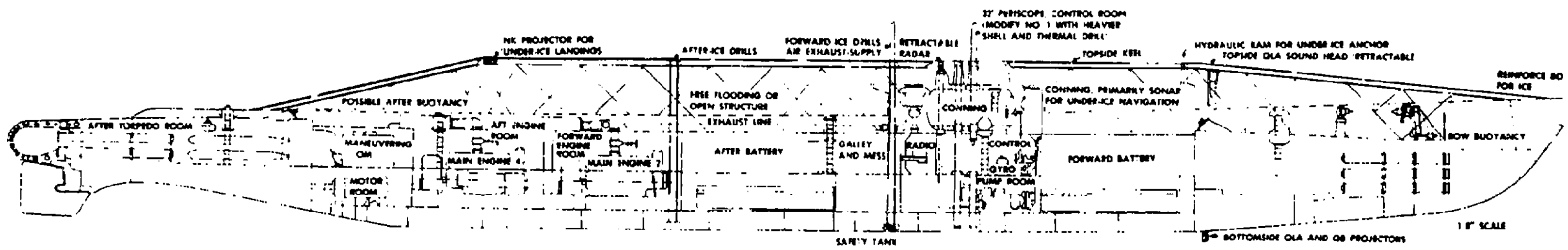


Figure 63. Modification of fleet-type submarine, deck plan.

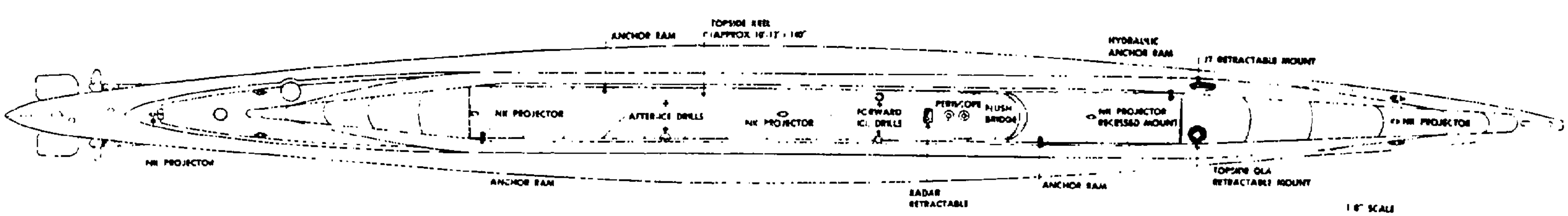


Figure 64. Modification of fleet-type submarine, longitudinal cross-section.

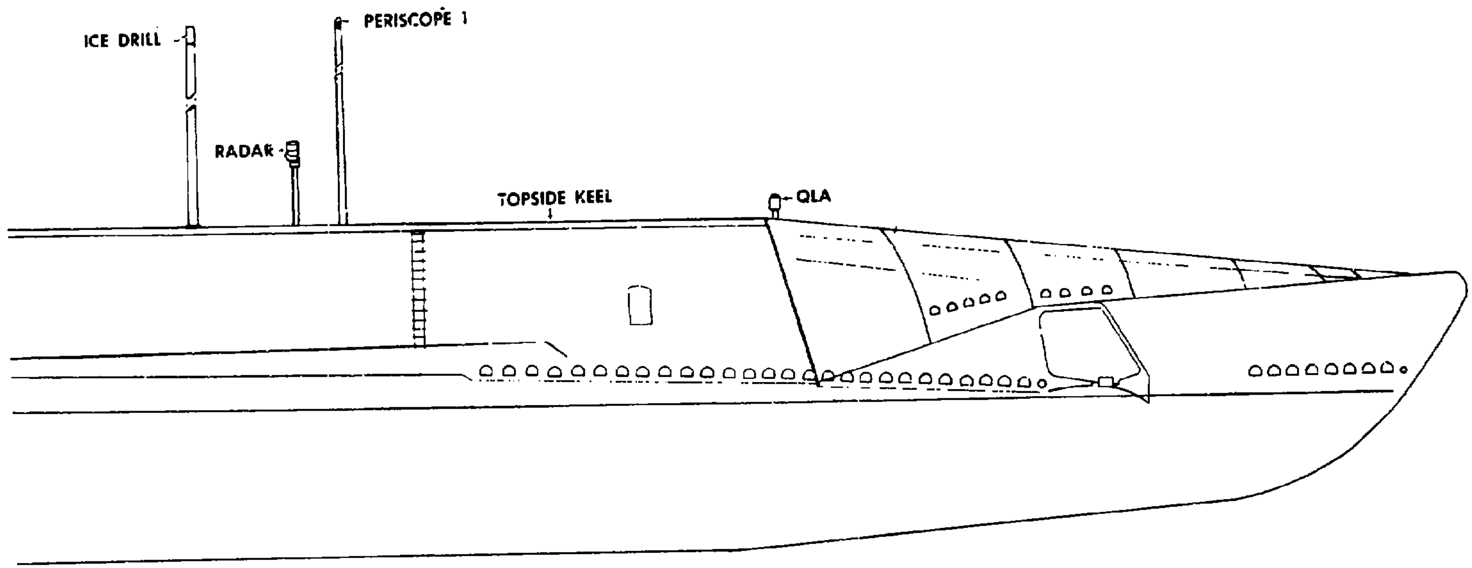


Figure 65. Turtleback of modified submarine.

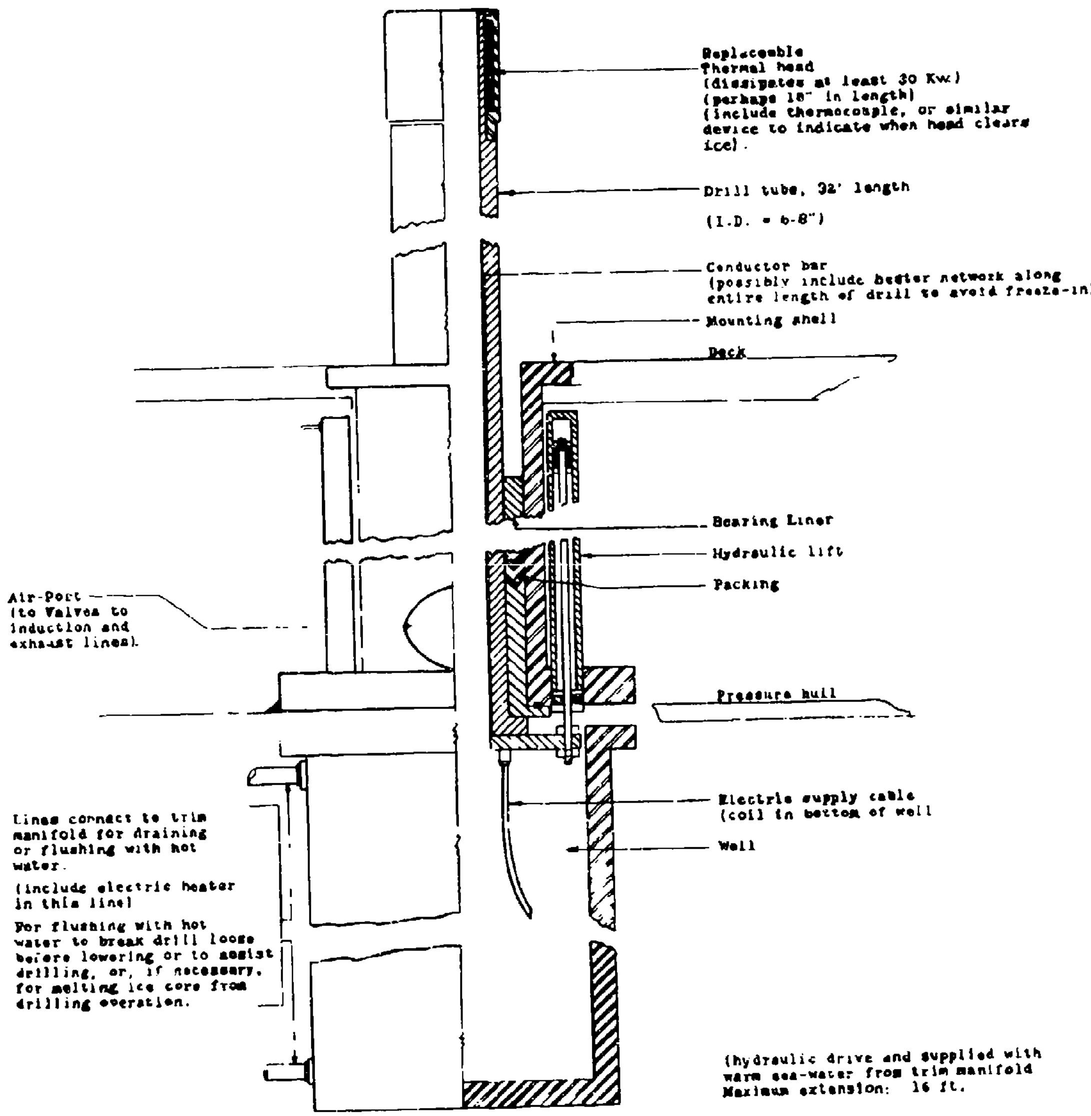
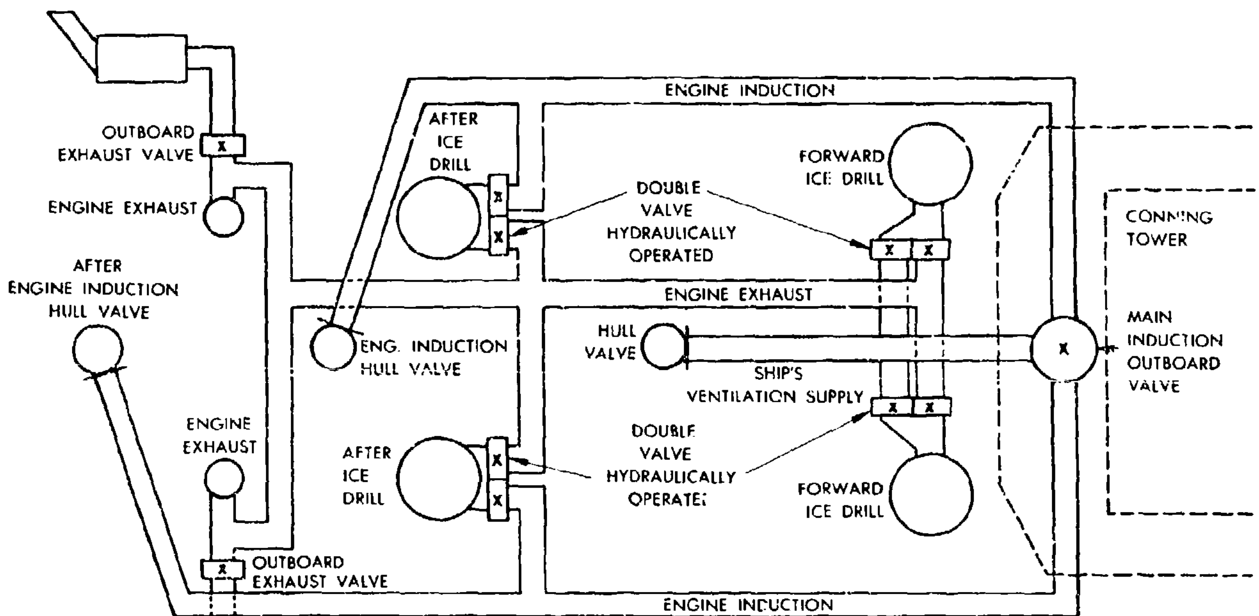


Figure 66. Electric thermal ice drill, schematic diagram.



ANY DRILL CONNECTED TO INDUCTION OR EXHAUST BY HYDRAULICALLY OPERATED VALVE. MODIFICATION REQUIRES ADDITION OF EXHAUST LINE, INTER-CONNECTION OF ENGINE EXHAUSTS AND THE VALVES AT ICE DRILLS.

Figure 67. Ice drill, exhaust-intake system.

is known as "the proverbial rigging of one's neck." However, it gives the reader something to "chew," and at least provides him with the superiority to pass judgment whether the scheme and initiator are *non compos mentis.*

The topside keel provides a flush deck, or "turtleback" for ascents in leads, and for resting under ice floes. It is a free-flooding superstructure with the deck at about the height of the present bridge. The deck area is approximately 1400 square feet, and the pressure on the ice, for example, at 50 tons positive buoyancy (after and bow buoyancy tanks blown) would be about 0.5 pound per square inch. The bow can probably be reinforced to give the vessel more power in surface maneuvering against ice.

The height of the "turtleback" deck permits the use of 32-foot periscopes in the control room, and 30-foot ice drills (16 feet exposed). Four ice drills are proposed which can be interconnected in any intake-exhaust sequence in order to provide flexibility and safety. The drills are heat-pressure type. Numerous schemes are possible; one example

is shown. The drill head is an electric resistance heater (chromalox, calrod, or similar) and is driven by hydraulic pressure, ship's hydraulic system, or trim pump. A core of ice will be floating in the tube at completion of the drilling and can be expelled by flow from the trim pump or can be lowered to the bottom of the drill chamber and melted. If the intake drill becomes frozen in the ice, hot water can be pumped into it during the lowering. The exhaust drill should remain free because of hot exhaust gases.

The minimum diameter of the drills is dictated by the required volume of air for engine supply. Air volumes and corresponding reductions of pressure in the boat are estimated for a 30-foot length of drill tube in Table VII.

TABLE VII

Inside Tube Diameter (inches)	Decrease of Pressure in Boat (inches of mercury)	Nominal Altitude Corresponding to Pressure Decrease (feet)	Volume of Air Delivered (cu. ft. per min.)
8	4	4000	12,000
6	4	4000	5,200
8	6	6000	14,000
6	6	6000	6,400

It is assumed that the scavenging blower on each engine requires approximately 5,600 cubic feet of air per minute. Obviously, the choice of tube size must further be based on material strength and availability.

The sonar equipments must be concentrated in the conning tower for directing under-ice navigation and ascents. The divorcement of equipments on the BOARFISH and CARP was a major difficulty. The QLA scanning equipment should be provided with both topside and bottomside transducers. The topside transducer should be tiltable in elevation for close-range scanning and to take advantage of particular thermal gradients that are encountered. Zenith ice scanners are not listed, nor are they a design contemplated at this stage of under-ice research. We are not in a position to recommend specifications for development of a zenith scanner. The tilting feature is useful in further work, and is recommended. Its use may lead to specifications for a zenith scanner.

Five type 808J topside fathometers distributed along the deck will give complete overhead coverage for all depths greater than 50 feet below overhead targets, and should furnish more than adequate information during under-ice landings and vertical ascents into leads.

Four hydraulically operated rams (e.g. six-inch diameter, 3-foot length) are suggested to assist, if required, the frictional drag during under-ice anchorings in the presence of currents.

Additions that are of value but not immediate priority are modification of one periscope to permit penetration through ice (heavy shell and thermal drill head), a large diameter thermal drill for personnel and equipment access to the surface, and a heat exchanger and hull insulation to provide hot-water storage in ballast tanks.

Consideration should be given to float mines for release in sequence from the after tubes, and tests made to determine the effectiveness of breaking a hole from below with explosives. A 54-pound wrecking mine lowered to about six feet below the lower surface of the ice is stated to be sufficient generally to crack a glacon 100 feet across and 30 feet thick.

Conclusion

A "turtleback" submarine is required before further under-ice work can be accomplished. The modification and its use is entirely experimental — the development of a new tool to investigate the unknown. The stage is somewhat analogous to the modification of the magnet for an outdated arc transmitter into the original cyclotron. A laboratory should have primary cognizance of the experiment, and the modification should be a direct expediency between laboratory, naval yard, and cognizant bureaus. The priority is most urgent in view of the very limited and fixed season, once each year, open to experiment, and because of the number of years that will elapse between experiment and a vessel for fleet operations.

TABLE VIII — Modifications for Turtleback Submarine

Modification	Fig. No.
1. Topside keel and flush deck fitted to pressure hull approximately at height of present bridge (open structure or plate — covered for streamlining).	63, 64
2. Reinforce bow for ice-breaking.	
3. Thirty-two foot periscopes to control room.	63
4. Four thermal ice drills, hydraulically controlled.	63, 64, 67
5. Induction and exhaust lines and valves for connecting ice drills.	67
6. Trim pump connections for control of ice drill, and electric unit for heating water (or some method of supplying hot water to drills for breaking loose after operation).	66
7. Concentrate sonars in conning, including:	
a. QLA: topside head, retractable and tiltable; bottomside head.	
b. QB type, echo-ranging unit (bottomside projector) for communication and iceberg reconnaissance.	
c. JT listening equipment.	
d. Five type NK or 808J topside fathometers for under-ice landings.	64
e. Short scale modification added to NGA fathometer.	
f. Experimental salinity-temperature recorder (CXJC-1), buoyancy-control recorder, and vertical accelerometer.	
8. Radar must be retractable and provisions made for securing the radio antenna below the "turtleback" during dives.	
9. Inboard vent for supply tank.	
10. After buoyancy tank to be used with bow buoyancy for under-ice anchorings.	63
11. Four hydraulic rams for driving into ice as under-ice anchors.	64
*12. Periscope modified with heavy shell and thermal unit to permit drilling through ice.	
*13. Thermal drill for personnel access to surface, 24 to 30 inches in diameter.	
*14. Heat exchanger on engine exhaust, and insulation of a ballast tank to provide storage of hot seawater.	
*15. Equip after torpedo room with under-ice mines.	

*Note: These items are of lower priority, and are not needed for next research phase.

APPENDIX A – NOTES ON QLA OPERATIONS CONDUCTED BY USS BOARFISH AND USS CARP*

USS BOARFISH, Arctic Cruise, 1947

While in the vicinity of the ice pack, the QLA was used on two surface runs into the ice pack, and four submerged runs under the pack. Four of these runs are described here, together with comments on the operation of QLA equipment.

1 AUGUST 1947

At 0900 headed into the ice at slow speed to test QLA with bottomside soundhead. We obtained ranges up to 600 yards on flat pieces of ice about 15 feet long and one foot out of water.

1439 – On this dive Rear Admiral A. R. McCann, USN, and party were aboard. We dove and planed down to 110 feet and headed under the ice. The most unfortunate equipment casualty of the trip occurred at this time. A key dropped out of a keyway in the topside QLA training motor coupling. This forced us to shift the QLA to the bottomside soundhead. With this compromise arrangement it was possible to see the ice on either beam, but, of course, not the ice ahead because of the masking effect of the hull. The ice which could be seen was detected at ranges out to 1200 yards and gave good indication on the QLA PPI. As we proceeded under the ice our only means of determining the presence and configuration of nearby ice was by the NK topside fathometer. By this we could determine the depth of ice above us when it was directly overhead. The average depth of ice under which we passed was 8 to 10 feet; these pieces were about 75 feet long. When we were about two and one-half miles into the field, an indication of a rapidly deepening piece of ice appeared on the NK fathometer. The depth of this piece reached 40 feet; at our keel depth, this left a clearance of only 13 feet over the periscope sheers. We went deeper – to 120 feet – then circled and headed out. In surfacing, a flat piece of ice skidded over the bow, another over the stern, and one off the port side of the cigarette deck. The downward pressure of this last one on the port wing antenna caused the after antenna stanchion to be bent forward.

4 AUGUST 1947

On this day the wind and sea were beginning to pick up from the southwest with sea force two and wind force three. In the morning we dove to 110 feet for another run under the ice. The ice at the edge of the field was mostly loose brash and slush which gave very poor indication on the QLA. After we got under the ice, QLA began to give good indications on ice about 6 feet deep. Later we passed under the edge of a piece of ice 40 feet deep from which the QLA obtained very strong echoes.

5 AUGUST 1947

The longest run under the ice, five miles, was made on this day. Due to the wind and sea conditions of the day before, the field was more closely packed than previously. We started in at 120 feet. Usual ranges on the QLA were 400 yards, with occasional echoes from large pieces at 800 yards. The ice averaged 10 to 15 feet in thickness and 1500 yards in horizontal extent. We passed under one piece of ice that was fifty feet deep. In general, the QLA ranges were not good; bottom return

* Notes prepared by A. H. Roshon, Jr. and F. Baltzly, Jr., FM Sonar Group, Development Division.

was quite strong at 400 yards. The BT trace showed several violent positive and negative excursions. These ice targets had echo characteristics very similar to shoal echoes rather than the ringing quality of solid targets. It appears that this effect was caused by signal return from the large areas of the rough bottom surfaces of the ice. Small isolated pieces of ice sound more like the solid targets we are used to, although, due to their odd and random configuration, they seldom present a smooth and symmetrical "blob" on the screen. We made tape recordings and took several photographs of the indicator screen on this run.

Conclusions

The multiplicity of targets in ice navigation presents a problem in sonar operation very similar to that encountered in mine evasion operations involving QLA. In this, an operator, even a thoroughly trained one, must concentrate so heavily on the details of operating the equipment, that it is most difficult for him to keep mental note of the broad picture and disposition of the submarine in her negotiation of the field. It was found, in the case of mine evasion tactics, that an "Evaluating Officer" was of invaluable aid in guiding the operator to report and hold contact on the *most important* targets. This officer stood near the QLA operator and viewed the screen with him, directing search areas and sectors, indicating targets to be concentrated upon as they were contacted, and directing the operator to discontinue contact when the relative position of the target indicated that it was of no further navigational concern. This effected an economy of operator effort, improving his efficiency and greatly reducing the possibility of a hazardous target being undetected. Perhaps the addition of an Evaluating Officer would be equally useful in ice navigation by QLA.

The need was again shown for the extreme desirability of a method or system of tilting the QLA soundhead. Primarily, this would permit range extension by counteracting the downbending of the sound beam. Secondarily, it would permit echo ranging in a vertical arc. This last might be developed into a means of determining, at least approximately, the vertical dimension of a piece of ice.

In reference to the equipment failures, the most extensive troubles were with the hoist-train mechanisms of the soundheads. Relatively, the greatest weaknesses of design lie in this section of the system. The Barco sliprings functioned without mishap throughout the trip. Their moistureproof design proved very desirable, and the continuous rotation which they afforded was a distinct advantage from the standpoint of tactical operation.

USS CARP, Arctic Cruise, 1948

The QLA-1 scanning sonar afforded horizontal bearing and range information, giving a good picture of the area round the boat to a range of 600 yards and more. It was found that most immediately important was information on ice out to a range of 300-400 yards. The resolution of the target portrayal was sufficiently good to enable the operator to differentiate between large, medium, and small pieces of ice. Even the general character of the pieces could be determined by the aural indications from the loudspeaker; the smooth, even pieces giving a bell-like echo and the rough, jagged pieces giving a rough (polychromatic) echo. Always, when surfacing after a run under

or around ice, the positioning of nearby ice very closely approximated the picture just previously presented by the QLA.

The commanding officer's report had this to say: "The QLA-1 in ranging on brash ice, glacons, and solid ice performed beyond all expectations. Lakes from and in which submerged operations were conducted had only about 90 per cent clear water with numerous pieces of rotten, brash, and glacon ice, each piece drifting at various speeds and directions to one another. Small bits of brash ice with little underwater surface were detected by the QLA-1 from ranges over six hundred yards to the minimum performance range of the QLA-1. . . . . . . Underwater excursions and submergence in lakes and from one lake to another in the ice field would have been impossible had the QLA-1 been unable to supply well in advance the location and range to open areas inside the lakes."

Within its limitations, the QLA-1 installation on board the USS CARP performed in excellent fashion. From the tactical standpoint, the PPI information provided by this scanning sonar was invaluable to the conning officer during the under-ice passages and the surfacings. The better results of the equipment during this summer's operations were due largely to more favorable and consistent water structure conditions.

Recommendations

As was pointed out in the report of the QLA operations in ice last year, the need for a tiltable soundhead is very evident. Each different tactical application of QLA scanning sonar suggests certain approaches to technical improvements, for example, increased bearing or range resolution, or perhaps a true bearing scale. From the standpoint of under-ice operation the strongest need for improvement is in the soundhead mounting. The several days of under-ice operation this summer has shown that QLA scanning sonar can, with satisfactory water temperature conditions, provide adequate and easily-interpretable azimuthal navigational information from ranges of about 100 yards out to about 700 yards. This applies to the equipment installed as it is on board the USS CARP. As mentioned before, the most immediately important information concerns the ice out to about 300-400 yards and obviously, the shorter range limitation resulting from the present method of mounting the QLA soundhead leaves the QLA blind at ranges of about 100 yards or less. Because of the fixed angle of the soundhead the minimum range limitation to surface targets increases with depth. The basic technique of QLA, which is FM sonar, permits a potential minimum range of a very few feet. The present minimum range limitation could be reduced very greatly by a system to vary the angle of the soundhead by tilting.

In general, when planning to use QLA scanning sonar for ice operation or mine evasion operation, the following installational considerations should be met:

1. The QLA soundhead should be raised above nearby objects to minimize cross-talk interference.
2. The QLA soundhead should have a tiltmount.
3. The QLA indicator should be installed with the viewing screen at eye-level height and with the plane of the screen vertical. This installation would permit the fullest advantage to be taken of the principal features of QLA scanning sonar — PPI indication with rapid azimuthal scan, and multiple target presentation. The conning officer should be able to view the screen directly, and should not have to wait for oral information from the operator.

APPENDIX B – CALCULATION OF SOUND FIELD – ROSS SEA*

Predictions of sound transmission can be made on the basis of four assumptions: (1) The attenuation of sound is nearly the same in the cold antarctic waters as it is in the warmer waters near southern California; (2) transmission in the antarctic seas can be classified by the same parameters as have been found useful locally; (3) the magnitude of the dependence of transmission on these parameters is the same; and (4) oceanographic factors (for example, wind, sea state, etc.) have no greater effect on transmission in antarctic waters than they do locally.

The last assumption is recognized to be questionable since upward refraction is prominent, and the condition of the sea surface is important. However, no quantitative data are available from which to evaluate the influence of the surface conditions. A hasty study has not revealed any temperature dependence of the attenuation of 24-kc. sound over the temperature region from 55° to 70° F., but the extrapolation to much colder water and to other frequencies may not be justified when quantitative data are finally obtained in polar seas.

Three examples of the vertical thermal structure and the associated ray diagrams are shown in figure B-1 (a), (b), and (c). The first example is a straightforward case of upward refraction. If the temperature remains constant, or increases, at greater depths, the entire main lobe of the sound beam will eventually be refracted upward and some portions of the beam may be channeled.

The second case shows a definite temperature increase with depth below the thermocline. This results in marked upward refraction at these depths, and a sound channel is formed. For this case all sound emanating within 4 degrees of the horizontal axis would theoretically be confined in the upper 450 feet of the ocean.

A sound channel also appears in the third case. A strong positive temperature from 50 to 80 feet lies over a negative gradient below which is another positive gradient. If the sound beam is taken to be 12 degrees wide, it is theoretically confined to the upper 400 feet of the sea.

Upward refraction is the dominant feature of these ray diagrams, and sound channels prevail near the surface. This is in agreement with observations.

It is of some interest to hazard quantitative guesses about sound attenuation in the antarctic area. Again, emphasis is drawn to the assumptions stated in the first paragraph, which may or may not be supported by future experimental results. Two hundred and thirty-nine bathythermograms taken from the USS HENDERSON (DD785) between 23 December 1946 and 5 March 1947 were used for this study. These data were taken in an area bounded by the 61st and 67th south latitudes and the 28th and 172nd east longitudes.

Transmission of 24-kc. Sound

The transmissions of sound at 24 kc. in deep water to a shallow hydrophone can be classified according to the depth, $D_{.3}$, at which the temperature first drops 0.3° F. below the surface temperature (cf. ref. 16) Transmissions to a hydrophone at a depth of 300 feet can be classified by the depth, D_5, at which the temperature has dropped 5° F. from its value at the surface (cf. ref. 17). These two temperature parameters are assumed to apply in the antarctic examples.

* Calculations prepared by M. J. Sheehy, Head of Analysis Section.

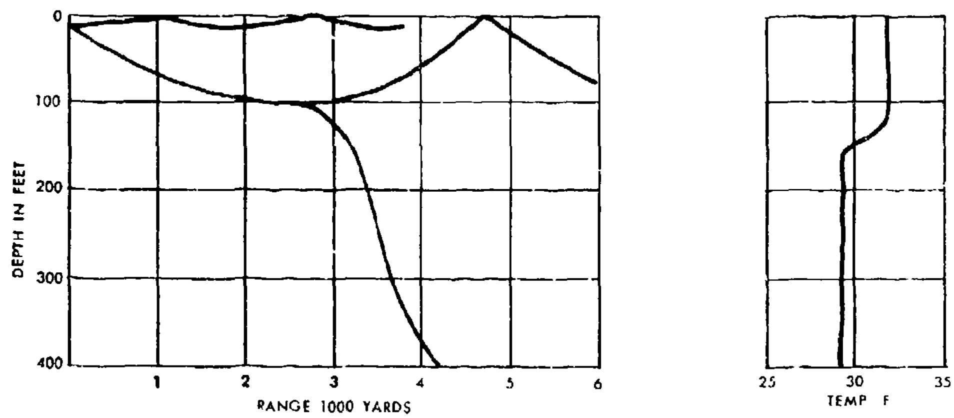


Figure B-1(a). Temperature structure and ray diagram, 20 January 1947, antarctic area.

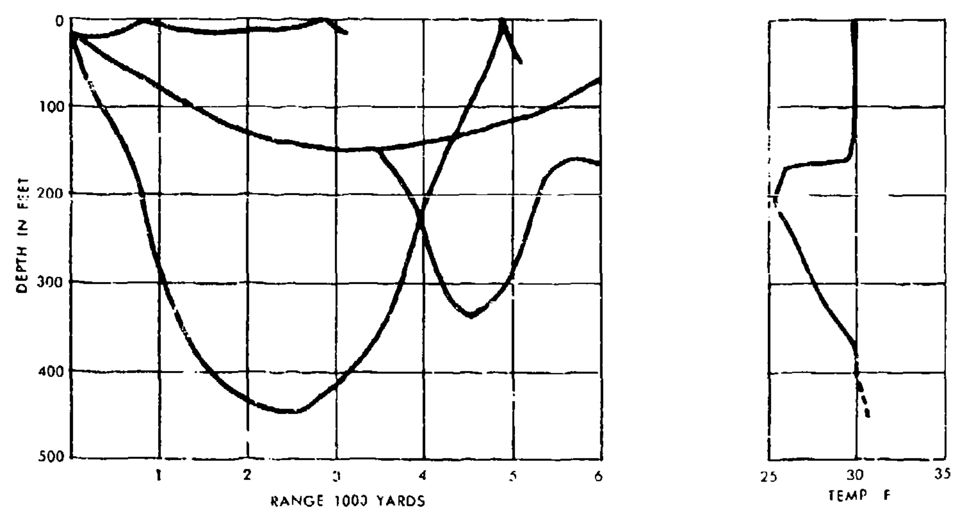


Figure B-1(b). Temperature structure and ray diagram, 23 January 1947, antarctic area.

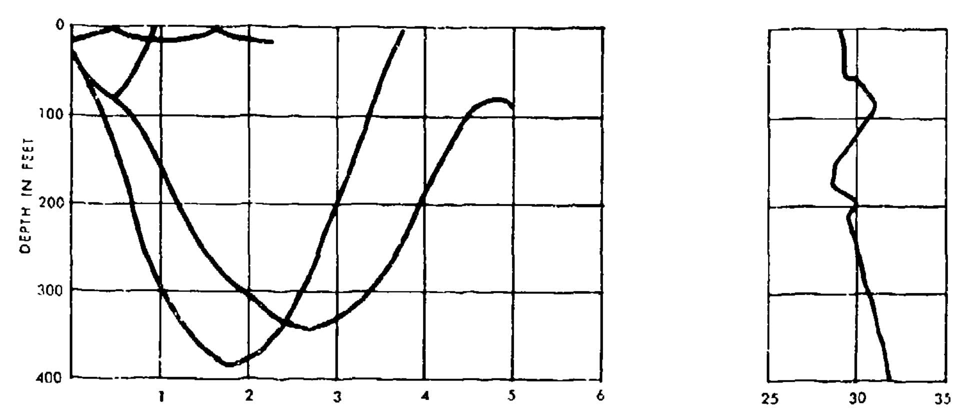


Figure B-1(c). Temperature structure and ray diagram, 13 February 1947, antarctic area.

The temperature data were first divided into six time intervals in order to judge if there were any marked diurnal variation in the thermal structure. D_2 was chosen to investigate this. Neither marked systematic trend nor much variation was found among the median values of D_2 for each interval. Therefore, the data are considered as a whole, and a cumulative distribution of the parameter, D_2, was obtained, which is shown in figure B-2 (a). The median value of D_2 is 116 feet, and the quartile deviation 36 feet.

It was reported in reference 9 that transmission to a hydrophone located between 16 and 50 feet below the surface could be classified by the parameter D_2. This is illustrated in figure B-2 (b).* From figures B-2 (a) and (b), it is seen that about 70 per cent of the time the average transmission is expected to be as good as that indicated by the uppermost curve of figure B-2 (b); i.e., an attenuation of approximately 4 db per 1000 yards. Ninety per cent of the time, transmission is expected to be at least as good as that represented by the second curve from the top, i.e. about 5 db per 1000 yards attenuation on the average.**

In view of the prevalence of upward refraction, the attenuations of 4 and 5 db per kiloyard are probably pessimistic estimates. Also, if the attenuation *should* depend upon temperature, the attenuation is likely to be lower in cold waters.

It is shown in reference 17 that transmssion of 24-kc. sound to a 300-foot hydrophone in deep water can be classified according to the parameter D_1 as shown in figure B-2 (c). A useful cumulative distribution of D_1 could not be obtained because most of the time bathythermograms were not taken to sufficient depth to determine actual values of D_1. However, in 70 per cent of the considered lowerings, it was established that D_1 was greater than 320 feet. Therefore, about two-thirds of the time the average transmission should be at least as good as that typified by the top curve of figure B-2 (c), i.e., an attenuation of about 5 db per kiloyard. It was noted in figures B-1 (a), (b) and (c) that a depth of 300 feet is often in a sound channel, which would result in still better transmission at this depth.

The minimum value of D_1 given by these data was 90 feet, and D_1 was less than 160 feet in only [illegible] per cent of the cases. The average attenuation is, therefore, expected to be less than 7.5 db per kiloyard at 300 feet practically all of the time.

Transmission at Sonic Frequencies

The transmission of 200, 600, and 1800 c.p.s. sound in deep water has been studied in temperate waters and has been reported in reference 18. The transmission anomaly, A, is shown to be given by the expression

$$-A = 10 \log 4 \sin^2\left[\frac{R_l}{2r}\left(1 - \frac{r^2}{R_r^2}\right)\right]$$

---

* Transmission anomaly is the intensity decrease in addition to that expected on the basis of the inverse square law of intensities.

** The statement combines an average attenuation and a percentage of time, and is, perhaps, confusing. The meaning is that during the time that D_2 is greater than the given value, the attenuation will vary but will have the stated average value. The strict presentation is the probability of observation of any given attenuation at any given time. This would involve considerations of the distribution of thermal structure and the fluctuation of the observed attenuation coefficients for any given thermal structure. This procedure is not warranted at this time.

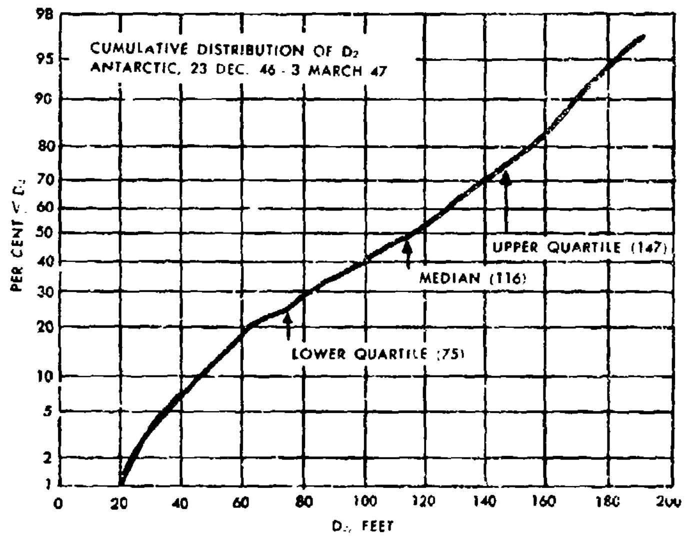


Figure B-2(a). Transmission of 24-kc sound.

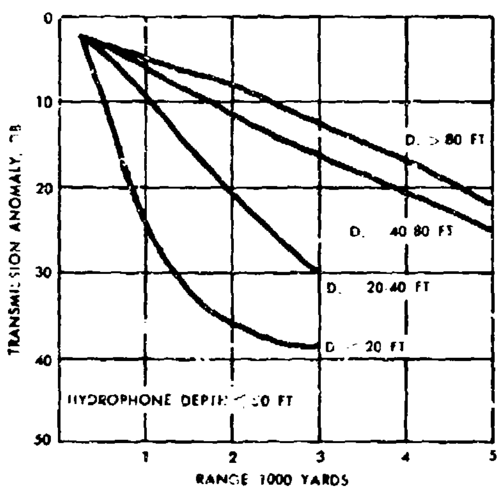


Figure B-2(b). Transmission of 24-kc sound.

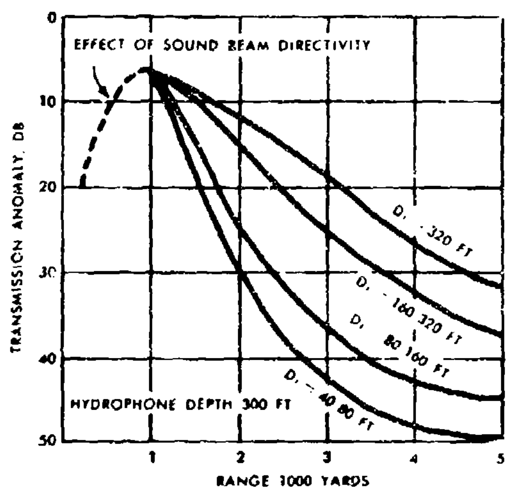


Figure B-2(c). Transmission of 2…

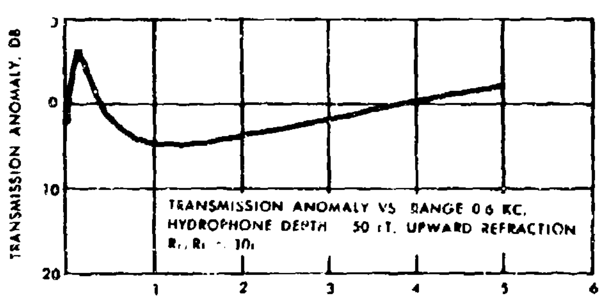


Figure B-2(d). Transmission of 24-kc sound.

where:

r is the range;

R_l is the range to the last predicted Lloyd mirror maximum (equals approximately $4ab/\lambda$ where a is the source depth, b the receiver depth, and λ the wavelength), and R_r is a refraction range given by

$$R_r = \left[\frac{b(a+b)c}{\Delta c}\right]^{1/2}$$

where c is the mean sound velocity and Δc is the amount by which velocity between the surface and source exceeds the mean velocity between the source and receiver.

The effect of upward refraction is to extend R_l; for example, if $R_r/R_l = 5$, R_l is increased by a factor of about 20. Beyond R_l the sound intensity decreases with range in accordance with the inverse fourth power law. The attenuation at these low frequencies is only a fraction of a db per kiloyard and so need not be considered here. As an example, figure B-2 (d) shows the transmission anomaly curve for 0.6-kc. sound from a source at a depth of 14 feet to a receiver at a depth of 50 feet for upward refraction conditions such that $R_r/R_l = 10$, i.e., $\Delta c = -1.1$ ft/sec.

It is noted that transmission should be relatively good for sound of sonic and supersonic frequency. However, target recognition is not necessarily high since in the presence of upward refraction surface reverberation makes the dominant contribution to the background level. Data are not available to assess quantitatively this contribution and its effect on target recognition.

APPENDIX C – SHIP HANDLING IN ICE*

Handling a submarine in an ice pack was an entirely new and different experience for everyone on board. Prior to the patrol, all available printed material on handling a ship in ice was studied. The best source of information seemed to be the translation of the Russian "Instructions for Handling a Ship in Ice".

In the following discussion it will be presupposed that a submarine will be operating in an area of growlers, brash ice, bergy-bits, icebergs, and pack ice without the aid of an icebreaker.

The very first requisite of the embryonic ice pilot is to develop a very healthy respect for the tremendous power of the ice. Never allow the peaceful appearance of an ice field to lull you into a sense of false security. On the other hand, don't fear the ice. A great deal of progress into ice can be made by a submarine capably handled.

First of all, never hit a piece of ice, however small, which can be avoided, regardless of the amount of maneuvering necessary to miss it. It is suggested that well qualified men be stationed in the maneuvering room and at the helm when operating in an area in which more than brash ice and occasional growlers are encountered; the speed at which bells are answered or the rudder put over quite frequently determines whether ice is hit or avoided.

The trim of the boat is another important consideration in ice. Here the submarine has an advantage over all other types of ships. When operating in pack with ice extending more than three feet below the surface, it is recommended that the stern

* Excerpt from the Patrol report of the USS SENNET, SS408.

be trimmed down so that the propeller guards are at least a foot and a half below the surface of the water. This depth is necessary because the pack is indented at the waterline, sometimes as much as five feet. The purpose of the flooding down is, of course, to protect the propellers from damage by pushing the heavy pack clear of the screws. With the submarine trimmed in this manner, the top blades of the propellers are ten feet below the surface of the water. It was found during the SENNET patrol that, except in close, heavy pack, 200 turns ahead and 133 turns astern could be made without damage to the propellers.

It is presumed, of course, that a submarine which is to operate in pack ice will have propeller guards, even in wartime. It is also recommended that an additional brace be installed on the propeller guards from the forward outboard corner to a point about ten feet forward on the hull. This additional brace is deemed necessary, not to give added strength to the present guards, which are considered sufficiently strong, but to streamline them and to prevent small floe jams forward of the guards. In the latter case, it is possible that a small floe may duck under the guards and hit the propellers.

The statement that the present guards are of sufficient strength is made in spite of the fact that the forward horizontal braces of both guards were bent considerably while the SENNET was being towed in heavy pack by the icebreaker. The damage occurred when the SENNET's stern swung into a heavy floe at a speed that would have been inadvisable under her own power in such a pack. The present guards are considered strong enough to fend the boat off any floe with which she might collide at reasonable speeds. It is desired also to point out at this time that the present guards afforded adequate protection to the propellers while the ship was under its own power. The major damage to the propellers was done when the stern of the boat swung into heavy floes while the boat was being towed. From the above, it is evident that some of our major damage occurred while we were under tow; but after having been NIPPED in the ice, it was the opinion of all hands that the most beautiful sight in the world at the time was the rear end of the COAST GUARD.

The propellers at present are nicked in several places, and their blades are bent. This damage was due, most probably, to small pieces of ice sliding below the propeller guards and hitting the soft bronze blades. To prevent similar damage it is recommended that submarines designated for operations in pack ice be fitted with steel propellers.

Another reason for trimming the boat down by the stern was to raise the bow as high as possible, giving it more rake from the waterline to the keel. This condition made it possible to ride up on, instead of boring into, floes projecting not more than three feet above the water. The amount of punishment from the ice that the bow could absorb without damage was amazing. When the boat had left the pack, there was no damage to the bow, as far as could be determined by visual inspection from a rubber boat, from the point eighteen inches above the waterline to the keel. Torpedoes were fired later without difficulty from both the forward and after tube nests.

A very minor point, but one which would undoubtedly be used to advantage many times in a pack, is that a collection of small bits of ice around the propeller guards may be cleared very quickly by reversing the propellers.

Always, when in a narrow lead, and especially when passing through a lead in a pressure ridge, keep way on the boat even at the expense of charging small floes. Once the boat is dead in the water, the ice will close in quickly and, before it is apparent, will nip the boat. It is particularly dangerous for a submarine to be caught in this manner in view of the fact that the ice will ride up over the tank tops, forcing the boat down. Although the SENNET's superstructure sustained several small casualties,

such as rivets popping out, it is believed that the tanks and hull of a submarine will absorb a great deal of pressure before being damaged.

When there is a choice of courses while proceeding through leads in a pack, choose one as nearly as possible in the direction of the wind. This is recommended because it is believed that ice fields normally move in a direction twenty degrees to the left of the wind in the Antarctic and twenty degrees to the right of the wind in the Arctic. However, because of their small sail area, submarines do not find the problem of crosswinds as serious as do most other types of ships. Crosswind leads in the ice, however, will tend to close much more rapidly than upwind or downwind leads.

The submarine's maneuverability is also an advantage. By twisting, the submarine can execute the many turns required to conform to the leads in the pack with much less difficulty than can other types of vessels.

When it is necessary to navigate through close pack made up of small floes, with the boat trimmed down by the stern, approach the pack at a speed of not over three knots. Use the rudder and engines freely to take the floes just off the stern. Stop engines after the boat has ridden up on a large floe and wait for it to break through. If the ice is too tough to be broken, go ahead slowly, pushing the floe ahead of the ship. Most of the time the floe will slide off to the side, but occasionally it will stay ahead of the ship for a considerable distance, acting as a fender for the entire vessel.

In conclusion, it is believed definitely that a submarine can operate independently without fear of damage in pack ice of less density than close, heavy pack.

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Report 88

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